

TP 6505E

APPLICATION OF FUZZY SET THEORY TO RISK ASSESSMENT IN THE TRANSPORTATION OF DANGEROUS GOODS

MAIN REPORT

Prepared for
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CITY OF TORONTO/YORK UNIVERSITY JOINT PROGRAM IN TRANSPORTATION

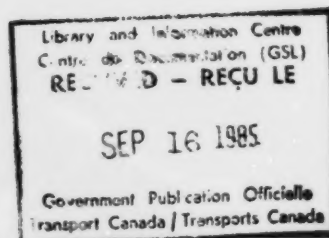
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17. Abstract This study evaluates potential for the application of fuzzy set theory to risk assessment in the transportation of dangerous goods. A review of the limitations of traditional objective probabilistic risk assessment methodologies is also made. The research on fuzzy set theory involved the development of a knowledge-based expert system to deal with public perceptions towards risk. The expert system was designed using linguistic rules intended to capture trade-offs between accident severity and accident frequency. Potentially, the model developed can provide part of the framework for assessing the acceptability of risks associated with alternative strategies for transportation of dangerous goods. A survey methodology was developed to collect data on public and "expert" perceptions of the membership of different quantitative measures within the domain of associated linguistic variables. The pilot survey administered in this study indicated that a great deal of emphasis will need to be placed on data collection in any future application of fuzzy set theory. In general, fuzzy set analysis cannot be viewed as a replacement for probabilistic analysis in risk assessment; however, it provides a means for including public and expert perceptions and attitudes within a comprehensive evaluation of transportation alternatives.			
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17. Résumé Ce rapport décrit la recherche qui a été faite sur l'application de la théorie des sous-ensembles flous à l'analyse des risques inhérents au transport des marchandises dangereuses. Il fait aussi le point sur les limites des méthodes probabilistes classiques d'évaluation des risques. La recherche sur la théorie des sous-ensembles flous a nécessité la mise au point d'un système "expert" doté de la base de connaissances voulue pour apprécier la perception que le public a de la notion du risque. Ce système, fondé sur des règles sémantiques, vise à apprécier toutes les nuances qui peuvent exister pour le public dans sa perception globale de gravité et de fréquence en matière d'accident. Le modèle établi permet, en principe, de répondre à une partie des questions que les spécialistes se posent concernant l'acceptabilité des risques associés aux diverses stratégies envisagées pour le transport de marchandises dangereuses. Une méthode de sondage a été mise au point; elle permet de déterminer à quelles expressions chiffrées d'une catastrophe ou d'un risque donnés correspondent, dans l'esprit du public et des spécialistes, les divers vocables descriptifs proposés. Un sondage pilote réalisé dans le cadre de cette recherche a montré l'importance que revêt la collecte d'une grande quantité de données, dans l'optique des applications futures de cette théorie. Celle-ci ne saurait remplacer totalement les méthodes probabilistes d'analyse, mais, en revanche, elle permet la prise en compte de la perception qu'ont le public et les spécialistes de la notion de risque et d'acceptabilité de ces risques, dans le cadre d'une analyse exhaustive des risques inhérents aux transports.		
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1. INTRODUCTION

1.1 NEED FOR RISK ASSESSMENT METHODOLOGIES

The risks associated with the transportation of dangerous goods has become a matter of public concern in recent years, mainly because of several major incidents in Canada and the United States. These incidents and the awareness of the increasing volumes of potentially dangerous goods being moved have created a climate where existing provincial and federal regulations are being reviewed and new legislation considered with the goal of managing the risks posed by the transportation of these materials.

Growing concern about the transportation of dangerous goods must also be viewed in the context of more general societal trends. There is ample evidence to suggest that western societies are becoming increasingly more "risk-conscious". Public attitudes and opinion that underlie this consciousness are manifest in a number of ways. In general, there is an increasing awareness of health hazards. Public pressure is mounting to reduce those health hazards that people are exposed to involuntarily (e.g. pollution, occupational hazards), while fewer people seem to take voluntary risks that may endanger their health (e.g. smoking). Moreover, there is growing concern about the gradual deterioration in environmental conditions that may not necessarily pose immediate threats but have grave health consequences in the long run (i.e. latent or delayed risks).

Similarly, the public has started to pay more attention to risks associated with the failure of technological systems. It is an inescapable fact, of course, that man-made machines periodically break down and cause material losses and environmental damage, as well as human injuries and deaths. In order to contain such risks within acceptable limits, safety standards have to be adopted in both the design and operation of technological systems. The conventional approach has been to establish such standards within an objective framework based on risk probabilities and benefit/cost trade-offs. However, it is often difficult to disregard values

and beliefs in order to remain strictly objective since the notion of "acceptable risk" always contains an element of subjectivity. Thus, even though objective conditions may remain the same, as values change and society becomes more risk-conscious, safety standards may have to be revised.

One of the major problems is that, because these concerns have only come to the fore in recent years, the methodologies and techniques of risk assessment and management have not been extensively developed. In many cases staff of federal and provincial agencies find themselves in the position of reacting to public perceptions of risk using only general information about the volume of movements of dangerous goods and the number of incidents that have actually occurred. Obviously there is a need for more effective methods of evaluating risks as well as the potential benefits and/or harmful effects of changes in the methods of transporting dangerous goods. Under the present circumstances, public agencies are in danger of either under-reacting, not taking into account the potential seriousness of the risks in areas where accidents have not yet occurred, or, where accidents have occurred, over-reacting with potentially harmful effects on the economy and on safety (eg. the diversion of dangerous goods from one mode of transport to another with possibly higher risk effects).

1.2 PRESENT METHODS OF RISK ASSESSMENT

In order to contain the risks associated with the transportation of dangerous goods within acceptable limits, safety standards have to be adopted in both the design and operation of transportation systems. As stated above, the conventional approach has been to establish such standards within an objective framework based on estimates of risk probabilities and benefit/cost trade-offs.

Most of the more thorough analyses of risk that have been undertaken in recent years have been based on one type or other of "fault tree" analysis. This type of analysis evaluates the relative probability of various types of accidents and their likely impacts. As such, it is based

on statistical analysis of the relative frequencies of different types of incidents and an evaluation of the potential impacts of each type of incident. Essentially current methods use the following formulation:

$$E(\text{Risk}) = \text{The sum over } i \text{ of Prob (release incident type } i) \times E(\text{Consequences of incident type } i)$$

Where: $E(\text{Consequences of incident type } i) = \text{The sum over } j \text{ of:}$

$$\text{Prob (environmental conditions type } j) \times E(\text{Consequences of incident type } i \text{ given environmental conditions type } j),$$

and: $E(x)$ is the expected value of variable x ,
 $\text{Prob}()$ is the probability of event y occurring.

In many cases the probability of a particular kind or type of incident is quite small, while the potential consequences can be very large. Thus, the valuation of the expected consequences of an incident is assessed by multiplying a very small number with a very large number, both of which have a large relative margin of error. As a result the confidence levels on the expected value of the consequences can be very broad.

In risk assessment studies, data limitations and the shortcomings of probability models are often overlooked. There is a tendency to rely on point value estimates of accident consequences (deaths, injuries, damages), even when there is considerable uncertainty about event probabilities. Moreover, there is a tendency to make policy choices which in many cases cannot be justified given the uncertainty of results (i.e. estimates with very wide confidence levels). All these observations point to the need for a critical evaluation of traditional probability models in risk assessment. The limitations of these models have to be recognized.

Another problem found with such analysis is that, although the purpose is to provide an objective evaluation of the risks involved, in practice these evaluations cannot be made completely objective. They

require subjective judgements to be made at several points. The fault tree analysis is "data hungry" and requires numerical values for probabilities and consequences to be inserted into the process. Often these are not available from historical analysis and even when available, the empirical parameters reflect past conditions and may not provide a good estimate of current and future risks.

Lately, the appropriateness of strictly technical, and what experts would claim to be strictly objective, approaches to risk assessment and safety standards is being increasingly questioned. The public appears to be reluctant to accept expert opinion at face value, particularly in cases where risks are associated with highly improbable but potentially catastrophic (i.e. low probability/high risk) events. In cases where the public's perception of risk exceeds the expert's measurement, decisions concerning the operation of transportation and other technological systems potentially involving dangerous goods become extremely sensitive.

Conflict between public perception and expert assessment can be attributed to a number of factors. Public perceptions are not always based on sufficient knowledge or are unduly inflated as a result of the media sensationalism that often surrounds major accidents and even debates on potential hazards. Alternatively, experts may be biased or disregard prevailing public opinion even when value judgements cannot be avoided within their objective framework of analysis. More often, however, conflict stems from the fact that what is desirable for the society at large may be totally unacceptable for a particular group bearing an unfair share of the associated risk. The allocation of benefits and costs is a fundamental problem in most public decision cases. It is also important in risk management, but is very difficult to treat objectively without invoking distributional value judgements.

As the public becomes more aware of technological risks but less confident in expert opinion, traditional risk analysis becomes an increasingly questionable basis for public decisions. Public perceptions become

as important in decision-making as expert analysis, and when the two are in conflict, neither the decision-maker nor the analyst has an effective means of resolving the conflict.

1.3 PURPOSE OF RESEARCH

As indicated above, there are a number of shortcomings associated with traditional risk assessment methodologies. The key shortcomings are as follows:

- o public perceptions about the acceptability of various types of risks are not included in the analysis;
- o objective estimates of risks developed using traditional approaches to risk analysis are actually based on a number of subjective inputs due to data limitations and changing conditions;
- o the data limitations and the lack of an adequate definition of "acceptable risk" in objective analysis can lead to an ad hoc or "seat of the pants" evaluation of alternative actions aimed at reducing the risks associated with the transportation of dangerous goods.

In recent years a methodology has been developed to handle vague or ambiguous concepts for application in human decision-making processes. This has been described as fuzzy set or possibility theory. This theory attempts to capture semantic ambiguity in a type of propositional calculus. The major difference from traditional methods of risk assessment is that fuzzy set theory does not attempt to "objectively" estimate the probabilities of different types of accidents or their effects, but rather directly measures people's perceptions of risks and the acceptability of those risks.

In light of these considerations, the objectives of this research study were as follows:

- o to review on a theoretical basis the limitations of traditional objective probabilistic risk assessment methodologies and to determine if those limitations can be reduced;
- o to determine how one can use fuzzy set theory to improve probabilistic and/or subjective analysis of the risks associated with the transportation of dangerous goods.

1.4 REPORT CONTENTS

In the remainder of this report, the strengths and weaknesses of each of the methodologies are reviewed and the methodologies are evaluated in terms of their respective roles in risk assessment. Suggestions are made with respect to potential improvements to the methodologies, both in terms of formulation and application. In the chapter following the review of the fuzzy set methodology, a potential evaluation framework is developed for the analysis of alternative transport strategies for the shipment of dangerous goods. The final chapter of the report presents a summary of the overall findings of the study and the recommendations of the study team on the further development of fuzzy set analysis.

In addition to the final report, two papers documenting the research conducted with respect probabilistic analysis and fuzzy set theory have been submitted under separate cover. These papers are entitled "Probabilistic Analyses And A Determination of Risk" and "Risk Policy Perception Associated With The Transportation Of Dangerous Goods: A Linguistic Rule Based Approach".

2. REVIEW OF PROBABILISTIC ANALYSIS

2.1 INTRODUCTION

Traditional risk models are probabilistic with expected value analysis constituting their core. Their policy applications fall within the general framework of normative decision theory.

These models of risk are generally based on the combination of two factors, the probability of the release of hazardous material (P_f) and the consequences of that release (C_f). Therefore,

$$R_i = f(P_f, C_f)$$

where R_i = the risk in a specified sub-section of the system

$$\text{and Risk} = \sum_i R_i$$

The sub-section, i , of the system identify the various types of potential failures and may also include sub-division of the route into sections with relatively similar characteristics (that is, sections where the risk is relatively constant in magnitude).

Potential failures (release sequences) are commonly identified through fault tree analysis, which readily facilitates an evaluation of the severity of an individual sequence and its probability of occurrence. This probability can be determined either through the use of historical data or by using information on the response of the system to normal and transport accident forces to determine when these forces will cause a system failure. The consequences of a release of hazardous materials depend upon the nature of the system failure, the location of the failure and the prevailing weather conditions. Therefore, the consequences of a specified failure type must be evaluated for all possible weather and location combinations.

2.2 REVIEW OF RISK ANALYSIS MODELS

A representative review of the literature on "objective" risk analysis was undertaken. The models of risk presented in the literature are similar to the general model discussed above. Simmons et al. (1973) examined the risk associated with spills of volatile, toxic chemicals, primarily chlorine. Risk was defined in terms of accident frequency and the consequence of expected fatalities. The expected number of fatalities were estimated from the population density in the vicinity of the spill and the area covered by a lethal dose. The model did not incorporate emergency response actions, such as evacuation, which in the case of chlorine spills have proven extremely effective in the prevention of injuries and deaths.

A risk model based on conditional probabilities was developed in a study for the U.S. Coast Guard (National Science Council, 1976). The model estimated the probability that a shipment containing hazardous materials would be involved in an accident with the release of hazardous material having a deleterious effect. The model was not applied, since much of the required data were found to be unavailable or extremely difficult to obtain.

A method of evaluating the risks on proposed modes and routes for the transportation of dangerous biological goods was developed by Garrick et al. (1969) for the U.S. Department of the Army. For a given mode of transport, the route was divided into a set of links and nodes. For each link or node the probability of a release of a specified magnitude was estimated from fault tree analysis. The potential consequences (i.e. number of infections) resulting from the release was determined from data on population density, dispersion, decay rates, aerosolisation and infectivity properties of the biological materials. Summing over all release magnitudes and over all links and nodes yields an estimate of the total risk associated with the particular mode of transport over a specific route.

An integrated risk analysis system developed at the University of Southern California incorporated a risk analysis model for the transportation of hazardous materials (Jones and Barrow, 1973). The model identified a number of accident types (eg. vehicular accident, loading/unloading spill, enroute container failure) and severity classes (eg. fire, explosion, toxic spill). The consequence measures used in the model were: dollars of property damage, number of injuries, and, number of deaths. For a given consequence measure, the risk was estimated by summing over all accident types and severity classes the product of the likelihood of an incident, by type and class, and the potential consequences associated with the incident. The development of the equations for both likelihoods and consequences is summarized in Phillipson and Schaeffer (1975) and are based on data available from the Hazardous Materials Incident Reporting System.

A similar model was used by Kloeber et al. (1979) in the assessment of air versus other modes for the transportation of explosives and flammable cryogenic liquids. Total risk for a given mode was found by dividing the route into segments where risk was expected to change, computing risks for each segment, and then aggregating to provide a risk value for the entire route.

Battelle-Pacific Northwest Laboratories have performed a number of risk assessment studies, all using the same methodology (Rhoades et al., 1978; Andrews et al., 1980, 1983). The assessment methodology used in their transportation risk studies evolved from a number of risk analysis models originally developed for use in the nuclear industry. The Pacific Northwest Laboratories (PNL) risk assessment model has been applied to the shipment of plutonium, spent fuel, uranium hexafluoride, gasoline, propane, and chlorine. The comprehensive nature of the PNL model and the application flexibility inherent in the assessment methodology accounts for its widespread use in the analysis of the risks associated with the transportation of hazardous commodities. For the above reasons, the PNL model was selected for a more detailed description to further our understanding of, and appreciation for, probabilistic risk models as well as highlight their strengths and weaknesses.

The model uses one fundamental equation:

$$R = \sum_i R_i \quad [1]$$

The total system risk R is the sum of the risks of all accidental releases as denoted by the subscript i . The risk of an individual release is the product of the consequences of the release and the probability of its occurrence. The risk of an accidental release can be expanded into two expressions which have more physical significance.

$$R_i = P(R_i) \times \sum_q (C(E_{iq}) \cdot P(E_q)) \quad [2]$$

Where:

$P(R_i)$ = the probability that the release sequence, i , will happen during transport. The amount and rate of material released is a characteristic of each release sequence.

$C(E_{iq})$ = the consequence of the material release from the i th release sequence, with q identifying the specific weather conditions existing at the time of release and the population exposed to the release.

$P(E_q)$ = the probability of encountering the particular set of weather conditions (q) within a specific population zone.

The expression $(C(E_{iq}) \cdot P(E_q))$ can be thought of as the consequence of material release under probabilistically weighted weather conditions and population distributions.

Four basic steps are followed in the evaluation of Equation [2]:

- o System Description;
- o Event Sequence Identification;
- o Event Sequence Evaluation;
- o Risk Calculation and Assessment.

System Description

The basic information on the shipping system to be analyzed is collected in this step. The industry being studied is characterized by gathering data on facility locations and industry shipping requirements. The commodities shipped, the shipping packages used, and the shipment quantities are determined for each transport mode. Information on the physical and chemical properties of the commodities transported are collected, and the population distributions and weather conditions along the routes are characterized.

Release Sequence Identification

The first task is to define the limits of the analysis by specifying the kinds of events that will be considered. For example, one specifies whether loading and unloading accidents will be considered or if acts of sabotage are within the scope of the analysis.

The sequences of events that could lead to a release of material from the transport vehicle are identified by the use of fault tree analysis and historical accident data. Fault tree analysis starts with the assumption that the undesired event has occurred and works backward to identify the sequences of events that must occur to cause this system failure.

Release Sequence Evaluation

This step consists of two basic parts: 1) estimation of event sequence probabilities; and 2) evaluation of the potential consequences of each event sequence. Event sequence probabilities are obtained by estimating the probability of each of the events that must occur to produce a system failure. This requires historical data and information on the response of the shipping system to normal and transport accident forces to determine the level of forces required to produce a system failure. Mathematical analysis or data available from testing programs are generally used to determine system failure thresholds.

Evaluation of the potential consequences of each release sequence requires an understanding of the type of failure, the characteristics of the material released, and the weather conditions and population distributions along the shipping route. The type and effectiveness of emergency response procedures are also incorporated into the evaluation.

Risk Calculation and Assessment

The information developed in the previous steps is combined to calculate the total risk and risk spectrum for the shipping system under study. Although the various components of risk (property damage, injury, death, etc.) could be estimated by the model, its application to date has focussed on predicting the expected number of fatalities per year. The risk spectrum is a graphical presentation of the interrelationship between the probability of occurrence and the magnitude of the expected consequences. The risk spectrum is a plot of the expected frequency (events/yr.) of events versus the number of fatalities that are predicted from those events. The curve is produced by summing event frequencies for various levels of consequence.

The results of the risk estimation phase are then analyzed to determine the primary contributors to the risk and to specify and evaluate alternatives that could reduce the system risk. Since the information to perform the risk assessment has been developed in discrete data blocks, sensitivity studies can also be carried out to test the effect on the system risk of assumptions and approximations that were made to develop key pieces of information.

2.3 DEVELOPMENT OF AN ALTERNATIVE MODEL

Traditional definitions of risk and risk analysis models have been less than adequate in a rare incident environment since the trade-offs between incidents with very low probabilities of occurrence but very high severity of consequences and incidents with greater probabilities of occurrence but lower severities of consequences are not considered within the

analysis. It would therefore appear that it is necessary to consider confidence estimates of the relevant parameters, and then to explore a range of possible outcomes to establish whether or not one particular policy is dominant.

Accordingly, the research undertaken in this study on probabilistic analysis focussed on developing an approach that would not produce point estimates of the risks of transporting dangerous goods but rather ranges of expected values of risk that reflect the uncertainty of our knowledge on the probabilities and consequences of dangerous goods accidents.

The initial model development focussed on assessing the risk of transporting hazardous goods by rail and considered only train derailment accidents. Although other modes of transport, such as truck or ship, were not addressed in the preliminary development phase, the potential for extending the model is discussed at the end of this section.

The nature of the hazardous commodity released in an accident is one of the primary determinants of the potential impact of the accident. Hazardous commodities may be characterized by general classification terms such as explosive, flammable, toxic, etc., or by a detailed list which itemizes individual commodities, such as propane, sulphuric acid, etc. There are many other factors that affect the incidence and severity of an accident such as train speed, weather conditions, track conditions, number and mix of cars, etc.; however, the number of such accidents and the accident documentation is insufficient in Canada to warrant their detailed consideration. This should be kept in mind since their omission will inevitably add an additional measure of uncertainty to the results obtained.

Structure of the Model

The proposed probabilistic model was constructed with a view to its application to risk assessment on a railway main line in an urban area. The model is based on the assumption that the main line rail network

in Canada can be considered as a homogeneous system with accidents assumed to occur over any portion of the network either uniformly or as a function of traffic volume. Given this assumption, the number of accidents involving the release of a dangerous commodity in a specified interval of time over a specified part of the network will have a Poisson distribution since we are dealing with a rare event environment. Thus, a single parameter, theta, defines both the expected number of accidents involving releases and the variance of the probability distribution.

Stated mathematically,

$$E(H_j) = V(H_j) = \Theta_j,$$

where H_j is the number of accidents involving release of commodity j (or classification j) in a specified interval of time and over a specified part (or all) of the network, and Θ_j is the "true" expected number of accidents involving release of commodity j in the time interval and track network under consideration.

The true value of the parameter cannot be ascertained, however, its value can be estimated from observed incidences. What is more important is that confidence intervals can be obtained around this point estimate and upper and lower bounds for the true value of theta can be determined. This is possible even if there are no incidences of release for a particular type of dangerous commodity over a specified time interval. The upper and lower bounds of a $100(1-\alpha)\%$ confidence interval for a parameter Θ_j can be calculated using a chi-squared distribution as follows:

$$j^L = (x/2) \chi^2_{2x, \alpha/2}$$

$$j^U = (x/2) \chi^2_{2(x+1), 1-\alpha/2}$$

Where $x \geq 1$ is the observed number of releases of commodity j on which the estimate is based.

If there are no incidents of release of commodity type j then we can estimate these bounds on the basis of the number of train movements involving commodity j . If there are n such movements involving no releases then a $100(1-\alpha)\%$ confidence belt is given by:

$$jL = 0$$

$$\theta_{ju} = \frac{F_{1-\alpha/2, 2, 2n}}{n + F_{1-\alpha/2, 2, 2n}}$$

The impact of some specified type (eg. deaths, injuries, property damage) from the release of a given type of dangerous commodity is also a probabilistic variable. Therefore, the overall potential impact of the transportation of dangerous goods over the time period and network segment in question is given by:

$$E(I) = \sum_j \theta_j E(I_j)$$

$$V(I) = \sum_j \theta_j [V(I_j) + (E(I_j))^2]$$

Where: I is the overall impact of a specified type (death, injury, etc.)

θ_j is the Poisson theta parameter for commodity type j

I_j is the impact of a single release of commodity type j

$E()$ represents the expected value

$V()$ represents the variance.

Any probabilistic statement on I must be made in the context of the confidence bounds on the theta values and the assumed forms and parameters of I_j .

This model, as is the case with traditional risk models, does not include an explicit accounting of the acceptability of various levels of risk. It is up to the decision-maker to include perceptions of risk acceptability as part of any evaluation process. The decision-maker can either

use his or her own perceptions on acceptability or his or her assessment of the public's perception of risk acceptability.

Key Assumptions

The probabilistic model developed in this study can be applied using a relatively limited amount of data if certain simplifying assumptions are made. These assumptions include:

- o uniform accident rates per train car-km over the rail network;
- o known distributions for the volumes of hazardous goods released given a release incident;
- o deterministic impacts associated with the different volumes of release.

Even with these assumptions, the uncertainty of prediction is generally of a high order due to the relatively rare occurrence of hazardous goods releases. The uncertainty of the predictions is broadened even further when simplifying assumptions are replaced with actual empirical data.

The simplifying assumptions made as part of the development of the probabilistic model illustrate one of the major shortcomings of this and other "objective" risk assessment models. As long as necessary data are available, risk analysis can remain objective in determining probabilities of events and their consequences. If all data requirements cannot be met, however, various assumptions must be made. These assumptions are often based on the informed opinion of individuals with considerable knowledge on the topic of interest. The simplifying assumptions may be treated as objective inputs into the model rather than being explicitly acknowledged as subjective inputs. As a result, probabilistic risk assessment that purports to be objective may actually be "less than objective" due to "expert" assumptions.

Sample Application of the Model

The model was applied using data on the transportation of dangerous goods along the CPR North Toronto Line. This application is intended to impart a flavour of the various issues surrounding the question of "how well can we estimate accident impacts" on this line. Basic data on accidents across Canada involving dangerous commodity leakages over a 2-1/2 year period starting in January 1982 was used to estimate the 95% confidence interval upper and lower bounds of the expected number of accidents. These results are summarized in Exhibit 2.1, broken down by primary classification of dangerous goods.

Also included in the exhibit are the "overall" confidence bounds obtained for all accidents collectively. As can be seen the bounds are extremely loose when the observed number of accidents is small, but tightens considerably for larger numbers of observed accidents involving release. An obvious result of the analysis to this point is that more years of data should be assembled to further tighten the respective bounds. A more detailed discussion of the data requirements of this and other probabilistic models, as well as a review of current data collection practices is contained in Appendix A.

These bounds obtained above must now be translated into corresponding bounds for the CPR North Toronto line under consideration. The scaling of the above bounds will include factors relating the track length and dangerous goods traffic on the CP North Toronto Line to the national track length and dangerous goods traffic. The CP North Toronto line is 9.6 km and as reported by Burton and Post carried 6478 carloads of dangerous goods in 1980. The national network involves about 67,000 km., and a total of 91,729 carloads of dangerous goods were shipped in 1983. The average trip length in 1980 was 923 km. Assuming that accident rates are uniform over the grid, a multiplying factor for accidents on the CP Line relative to the grid is $(6,478 \times 9.6) / (91,729 \times 923) = .0007345$.

The bounds from Exhibit 2.1 can then be re-expressed for a one year interval for the CP Toronto line using this factor, with the results summarized in Exhibit 2.2.

These results would be substantially more accurate with respect to each of the classes if class shipment details on the CP Line were expressed relative to analogous shipments on the national grid.

An analysis of impacts was then considered with respect to measures involving zones for building damage, personal injury and death. This quality of information is lacking in the Canadian context, so results from the U.S. were adopted. The relevant data taken from the U.S. as well as computed values for the respective means and standard deviations are presented in Exhibits 2.3 through 2.6 for the various dangerous goods classes. In Exhibit 2.7 we give the computations leading to the determination of $E(I)$ and $V(I)$ for each of the 3 impact types - the results are presented using both "extrema" of j as given in Exhibit 2.1.

To demonstrate how these results might be used, let us consider the impact representing death. This is expressed in terms of a lethal zone (in km^2); to get predictions for the number of deaths, other factors including population density and individual death propensity would have to be incorporated. Specifically, estimates of the number of deaths could be predicted as follows:

$$E(\text{deaths}) = \frac{\text{Lethal zone area} \times \text{population density}}{\text{Overall death propensity}},$$

Where: Overall death propensity is equal to the weighted average of the individual death propensities of the population of the area.

The individual death propensity could be a function of age or other demographic characteristics or could be equal across all individuals, depending upon the nature of the incident.

Using the surrogate of lethal zone in our discussion we observe from Exhibit 2.7 that a 95% confidence interval for the expected lethal area is $(475.73, 4405.92) \times 10^{-8} \text{ km}^2$ with corresponding standard deviation interval $15370, 72718) \times 10^{-8} \text{ km}^2$. Since the coefficients of variation at each extreme (standard deviation/mean) are so very large a gamma fit would be unsatisfactory; therefore let us try a lognormal distribution. At the lower bound levels we then have the relations:

$$475.73 \times 10^{-8} = e^{\mu + \frac{1}{2}\sigma^2} \quad 16370 \times 10^{-8} = e^{2\mu + \sigma^2} (e^{\sigma^2} - 1)$$

which can be solved for μ and σ yielding $\mu = -28.04$, $\sigma = 3.97$. The corresponding values at the upper level are $\mu = -16.45$, $\sigma = 3.58$. We can then compute various risks for each in terms of probabilities that the size of the lethal zone exceeds specified amounts, as shown in Exhibit 2.8

The results of Exhibit 2.8 imply that if we assume a population density of 1,000 persons/km² and an overall death propensity of 100% then over a period of 100 years the chance of at least one death occurring ranges from 0% to 10.7% and the chance of at least 10 deaths occurring ranges from 0% to 2.1%. Over the next ten years the chance of at least one death occurring ranges from zero to one in fifty.

The direct interpretation of this sample listing is that the "true" probability lies anywhere between those based on the lower bounds and those based on the upper bounds. For the sample impact measure used these ranges are quite broad. In fact, these were based on the assumption that a host of other parameters are estimated from available data in a precise fashion. Allowing these other dimensions of variability to enter into the risk assessment modelling and computation would result in a further broadening of the prediction range.

If we relax the assumption that accident rates are uniform over the grid and introduce new dimensions such as track condition and geometrics and train speed then the observed accidents are disaggregated over a number of potential situations and any confidence bounds for different impacts such as deaths, injuries and property damage are broadened.

The prediction range would be broadened even further if it were not assumed that the impacts of various levels of release of different classes of dangerous goods could be defined deterministically. In reality, the impact of a specific level of release of a dangerous commodity is variable since it is dependent on probabilistic factors such as weather, physical conditions at the accident site and the effectiveness of impact control measures introduced at the time of the accident.

Areas Requiring Further Development

The proposed probabilistic model has been developed in the context of the transportation of dangerous goods by rail. The application of the model to the truck mode would require a review of some of the basic assumptions underlying the model. In particular, the assumption of homogeneity over the network, or even a subset of the network, would likely be inappropriate for the truck mode. It may be necessary to develop a series of models or estimate an array of parameter values relating to different types of road sections.

Additional development is also required for the probabilistic analysis of accident consequences, particularly with respect to the potential impacts of improved response techniques and programs, since such programs, unlike the weather, other environmental factors and physical and temporal characteristics of a dangerous goods accident, are under a community's direct control.

2.4 ASSESSMENT OF THE PROBABILISTIC APPROACH

The prime motivator for the preceding review and analysis was the question of whether objective probabilistic modelling can be used meaningfully to determine the risks associated with the transportation of dangerous goods, and to assess the feasibility of comparing alternative routes or modes of transport on the basis of the risks.

The Pacific Northwest Laboratories risk assessment model reviewed in Section 2.2, and the risk analysis approach developed in the preceding section represent two distinctly different approaches to assessment of the risks involved in the transportation of dangerous goods.

The major strengths of the PNL risk assessment methodology derive from the comprehensive, systematic approach adopted and the inherent flexibility offered by the detailed breakdown of the risks into discrete, identifiable event sequences. Estimation of the probabilities associated with each event that must occur to produce a system failure readily facilitates model sensitivity and alternative scenario testing. For example, one could test the impact of increasing the transport container's strength, or reducing vehicle speeds by altering only those event probabilities affected by the improvements. Likewise, the effectiveness of improved emergency response procedures could be analyzed by re-evaluating only that subsection of the model. The model also offers limited transferability potential for some of the major sub-components. The sequences of events that could lead to a release of hazardous material from a derailed tank car are the same whether the commodity transported is chlorine or propane (given that both are transported in the same type of tank car).

The complex nature of the PNL assessment methodology can also be cited as a weakness of the model. The model requires a considerable data base to be applied successfully. Detailed data on system performance, accident causes, accident forces, vehicle characteristics, weather conditions, population distributions, etc., are required. The large data requirements, combined with the limited data availability, necessitate numerous assumptions and value judgements. The complexity of the model not only obscures many of the assumptions, but makes it very difficult to assess the cumulative effect of all the assumptions on the final model results. The use of a single point estimate of total risk (i.e. deaths/yr.) is also a shortcoming of the model. Without some qualification attached to the final risk estimate, in the form of upper and lower bounds, the confidence in, and usefulness of, the estimate is diminished. The PNL model would also be very costly and time consuming to apply which further detracts from its usefulness.

The proposed probabilistic approach recognizes the severe restrictions placed on risk assessments in a rare event environment by the lack of suitable data. Not only are the number of occurrences very low, but the data collected from the limited accident/incident sites is generally not comprehensive enough for modelling purposes. The proposed methodology focusses, not on a point estimate of risk, but on the specification of reasonable limits associated with the risks of transporting dangerous commodities. This represents a major departure from traditional risk assessment models.

There are also a number of weaknesses in the proposed approach. Problems arise in using the model if there are changes in the "time" values of the probabilistic parameters due to changes in regulations governing the transportation of dangerous goods or in equipment design and operations. If there is reason to believe that the probability distributions are not static, it may not be possible to use all of the historical data available on releases in order to estimate the parameters. As indicated earlier, the availability of data has a substantial impact on the "tightness" of the bounds on the parameter estimates. Other simplifying assumptions in the model development also limit the model's sensitivity to changing system attributes.

It has been clearly demonstrated that when we are dealing with rare events, characteristic of the issues dealt with here, the uncertainty of predictions based on these few counts is generally of a high order. So much so, in fact, that definitive statements about actual risks are virtually impossible to state. Furthermore, because of these features it is also naive to expect that a statistically significant difference will result in any comparison of alternative routes or modes. In that instance, the results would be so dramatically biased in favour of one choice that the superior route would be obvious without any deep analysis. Finally, it should be noted that objective probabilistic modelling does not resolve the problem of trade-offs between the risks associated with releases which have a low probability of occurrence but high level of impacts and those with a higher probability of occurrence but a lower level of impacts.

Exhibit 2.1

Canadian Train Derailment Accidents Involving Dangerous Goods:
Jan. 1982 - June 1984

Class	Primary Classification of Dangerous Goods	No. Accidents (over 2.5 years)	θ_j^L (over 2.5 years)	θ_j^U (over 2.5 years)
2	Flammable or Poisonous Gases	4	1.088	10.24
3	Flammable & Combustible Liquids	9	4.122	17.10
6	Toxic Substances	1	.025	5.57
8	Corrosive Substances	<u>5</u>	<u>1.620</u>	<u>11.65</u>
	Overall	19	11.438	29.64

Exhibit 2.2
 Θ_j for the CP Toronto Line (per year)

Dangerous Goods Classification	Θ_j^L ($\times 10^{-4}$)	Θ_j^U ($\times 10^{-4}$)
2	3.20	30.09
3	12.11	50.24
6	.07	16.36
8	4.76	34.22
—	—	—
Overall	33.61	87.18

Exhibit 2.3
Impacts for Dangerous Goods Class 2

Amount Released (gallons)	Probability	Lethal Zone ($\times 10^{-4}$ km ²)	Injury Zone ($\times 10^{-4}$ km ²)	Building Damage ($\times 10^{-4}$ km ²)
0 - 1000	.27	2	2	10
1000 - 5000	.08	7	75	17
5000 - 10000	.12	13	170	28
10000 - 25000	.26	26	340	48
25000 - 50000	.21	48	680	80
50000 - 100000	.05	89	1200	130
Mean		23.51	312.14	42.55
Standard Deviation		22.1	261.69	32.29

Exhibit 2.4

Impacts for Dangerous Goods Class 3

Amount Released (gallons)	Probability	Lethal Zone ($\times 10^{-4}$ km ²)	Injury Zone ($\times 10^{-4}$ km ²)	Building Damage ($\times 10^{-4}$ km ²)
0 - 1000	.27	1.1	7	1.1
1000 - 5000	.08	4.4	31	4.4
5000 - 10000	.12	10	63	10
10000 - 25000	.26	23	140	23
25000 - 50000	.21	45	280	45
50000 - 100000	.05	90	480	90
Mean		21.06	128.73	21.06
Standard Deviation		22.30	131.27	22.30

Exhibit 2.5

Impacts for Dangerous Goods Class 6

Amount Released (gallons)	Probability	Lethal Zone ($\times 10^{-4}$ km ²)	Injury Zone ($\times 10^{-4}$ km ²)	Building Damage ($\times 10^{-4}$ km ²)
0 - 1000	.27	2.9	25	4.5
1000 - 5000	.08	15	140	11
5000 - 10000	.12	40	350	24
10000 - 25000	.26	100	870	50
25000 - 50000	.21	220	2000	100
50000 - 100000	.05	480	4400	190
Mean		100.58	904.15	47.53
Standard Deviation		115.01	1052.00	46.91

Exhibit 2.6

Impacts for Dangerous Goods Class 8

Amount Released (gallons)	Probability	Lethal Zone ($\times 10^{-4}$ km ²)	Injury Zone ($\times 10^{-4}$ km ²)	Building Damage ($\times 10^{-4}$ km ²)
0 - 1000	.27	.6	48	.6
1000 - 5000	.08	3.7	310	3.7
5000 - 10000	.12	10	883	10
10000 - 25000	.26	27	2400	27
25000 - 50000	.21	65	6100	65
50000 - 100000	.05	150	14000	150
Mean		29.08	2678	29.08
Standard Deviation		35.45	3325	35.45

Exhibit 2.7

Means and Variance of Impacts

Dangerous Goods Classification	Θ_L $\times 10^{-4}$	E(Lethal) $\times 10^{-8} \text{ km}^2$	V(Lethal) $\times 10^{-8} \text{ km}^4$	E(Injuries) $\times 10^{-8} \text{ km}^2$	V(Injuries) $\times 10^{-8} \text{ km}^4$	V(Damage) $\times 10^{-8} \text{ km}^2$	V(Damage) $\times 10^{-8} \text{ km}^4$
2	3.20	75.23	.38	998.85	53.06	136.16	.91
3	12.11	255.04	1.14	1558.92	40.71	255.04	1.14
5	.07	7.04	.16	7.00	.16	3.32	0.3
8	4.76	138.42	1.00	12750.70	8678.18	138.42	1.00
Totals		475.73	2.68	15315.47	877.11	532.94	3.08
Class	Θ_j^u $\times 10^{-4}$	E(Lethal) $\times 10^{-8} \text{ km}^2$	V(Lethal) $\times 10^{-8} \text{ km}^4$	E(Injuries) $\times 10^{-8} \text{ km}^2$	V(Injuries) $\times 10^{-8} \text{ km}^4$	E(Damage) $\times 10^{-8} \text{ km}^2$	V(Damage) $\times 10^{-8} \text{ km}^4$
2	30.09	707.40	3.57	9392.29	498.97	1280.33	8.57
3	50.24	1058.06	4.72	6467.40	168.89	1058.06	4.72
6	16.36	1645.35	37.39	1636.00	38.00	777.59	7.30
8	34.22	995.11	7.20	91665.11	62395.28	995.11	7.20
Totals		4405.92	52.88	109160.80	63101.14	4111.09	27.79

Exhibit 2.8

Probability of Exceeding Lethal Zone Size

Lethal Zone ($\times 10^{-8}$ km ²)	Lower Bounds	Higher Bounds
1	.0078	.709
10	.0013	.464
100	-	.230
1000	-	.107
10000	-	.021

3. REVIEW OF FUZZY SET ANALYSIS

3.1 INTRODUCTION

Traditional approaches to risk analysis are probabilistic in nature. Decisions that are made within this framework are based on trade-offs between the costs of alternative courses of action and reduction in the expected value of damages (or risks). The reliability of such benefit-cost calculation depends to a large extent on the quality of available data. Regardless of how serious the difficulties may be in this regard, many advocates of this approach would defend at least the objectivity of their methods and argue against any reliance on subjective considerations in the decision-making process.

In practice, however, this approach advocated by "objectivists" is rarely followed. Most if not all, decisions are influenced if not dictated, by subjective considerations. In risk management, public acceptability is often on overriding consideration. Public perception of risk is, of course, not necessarily based on objective facts. Public's preference for a particular course of action may not coincide with the analyst's choice based on probabilistic expected value analysis. In practice, such conflicts are extremely difficult to resolve, and in most instances, public preferences would dictate the outcome. Thus, the rational course of action is not to "purify" the allegedly scientific and objective risk analysis methods from necessarily subjective public perceptions, but to "incorporate" those perceptions to a risk assessment and management framework, which in principle does not pose a methodological conflict between the "objective" and the "subjective".

In an attempt to understand public perception of risk (or to determine acceptable risk levels), two major approaches have developed in the literature, revealed preferences and expressed preferences. A major distinction between the two approaches is the experimental technique: the former involves an assessment of perceived risk from the observation of

behaviour, the latter requires that people respond to a series of questions and therefore verbally express their preferences and perceptions.

Clearly, the method used can have a significant influence on the results. An advantage of the revealed preference approach is that it deals with public behaviour rather than attitudes. However, the underlying assumption of the approach is that past behaviour is indicative of present preferences. There is no reason to expect that this is always true. The expressed preference approach is influenced significantly by the formulation and wording of questions and by the selection of participants in the study. Despite the limitations of these two techniques, to date no better means have been found to evaluate the decision processes where risk perception is involved.

The research undertaken in this study represents an attempt to apply "fuzzy set" or possibility theory. This is intended to provide an alternative expressed preference approach to determining perceived risks. Specifically, the research involved the development of a knowledge based expert system that could deal with public perception towards the risks of transporting dangerous goods. The model can potentially provide a methodology for including public and expert perceptions in a structured manner within an evaluation process dealing with alternatives in this area. The expert system that was designed using linguistic rules is intended to capture trade-offs between accident severity (measured in total cost to community) and accident frequency (i.e. rate of occurrence) in the transportation of dangerous goods. Furthermore, the model can potentially provide a framework to assess acceptability of risks associated with alternative strategies (i.e. mode or route selection) for transporting dangerous goods.

3.2 THE CONCEPT OF FUZZY SETS AND INFERENCE STRUCTURES

One of the fundamental tenets of modern science has been that a phenomenon cannot be claimed to be well understood until it can be characterized in quantitative terms. This forms the basis of on the one hand

respect for what is precise, rigorous and quantitative, and on the other, distrust for what is fuzzy, unrigorous and qualitative. The use of quantitative methods expanded throughout most fields of human knowledge in mechanistic systems such as mechanics, physics, chemistry, etc. It has been argued by L. A. Zadeh (1975), however, that the same cannot be said about humanistic systems such as philosophy, psychology, literature, law, politics, sociology, etc. Zadeh (1975) further states that the ineffectiveness of quantitative methods "in dealing with humanistic systems is a manifestation of what might be called the principle of incompatibility - a principle which asserts that high precision is incompatible with high complexity".

Faced with the complexity of our post-industrial socio-economic systems, linguistic variables have a wide range of potential applications. The motivation for linguistic characterization is that they are less specific than numerical variables. If the values of a numerical variable are visualized as points in a plane, then the values of a linguistic variable may be depicted as ball-parks with fuzzy boundaries. Linguistic variables with the fuzzy set theory representation acquire the ability to serve as a means to approximate characterization of phenomena which are too complex or too ill-defined to be described in precise terms.

Within the context of this study on risk perception associated with the transportation of dangerous goods, examples of linguistic variables include SMALL or BIG costs to community, INFREQUENT or FREQUENT occurrence of accidents involving the transportation of dangerous goods, and ACCEPTABILITY or UNACCEPTABILITY of the risks. They approximately characterize the phenomena which are too complex or too ill-defined to be specified in precise terms.

The basic concept of fuzzy sets can be briefly stated in the following manner. Let X be a classical set of objects, called the universe whose generic elements are denoted by $x \in X$, where " $\in$ " is short for "member of". The membership in a classical subset A of X is often viewed as a characteristic function μ_A from X to $(0,1)$ such that:

$$\begin{aligned} \mu(x) &= 1 \text{ iff } x \in A, \\ &0 \text{ iff } x \notin A. \end{aligned}$$

Where:

"iff" is short for "if and only if"
(0,1) is called a valuation set (two valued)
 $\notin$ is short for "not a member of".

If the valuation set is allowed to be the real interval (0,1) (infinite valued), A is called a fuzzy set. $\mu_A(x)$ is the grade of membership of x in A. The closer the value of $\mu_A(x)$ is to 1, the more it belongs to A. Clearly, A is a subset of X that has no sharp boundary. A is completely characterized by the set of pairs:

$$A = \{(x, \mu_A(x)), x \in X\}.$$

The application of the basic "fuzzy set" concept to an accident context is straightforward. If fuzzy sets A and B are defined as BIG and FREQUENT, then $\mu_A(x)$ and $\mu_B(x)$ represent the membership of the accident state x in those two fuzzy sets. There could then be a correspondence between the fuzzy membership functions and the degree to which the public perceive a given accident state (e.g. accidents resulting in \$5 million damage every 3 years) to be BIG or FREQUENT.

In order to combine these concepts in a decision context based on "acceptability of risk", an inference structure has to be developed. Consider the case where a risk policy rule is stated as follows:

"If the severity of costs to a community is perceived to be SMALL and the occurrence of the accidents is perceived to be INFREQUENT by the public for a particular mode of transportation and for certain dangerous goods, then the risk policy associated with the said mode of transportation for the said dangerous goods ought to be ACCEPTABLE by the public "(Note: this normative statement itself can be based on expressed perceptions: i.e. perceived to be ACCEPTABLE. The statement implicitly assumes that the public evaluates the

acceptability of the risk relative to some perceived level of benefits or need for the transportation of dangerous goods).

Such a statement has the form of a fuzzy inference structure:

"if A and B then C"

Where A would indicate the perceived severity of costs to the community, B the perceived frequency of accidents, and C the perceived level of acceptability of risks.

This provides a suitable inference framework when:

- o the severities of costs to community are expressed in linguistic vague and ambiguous terms such as BIG and SMALL;
- o the occurrence of accidents are expressed in linguistic terms such as INFREQUENT and FREQUENT; and,
- o the public expresses their concern about these circumstances in linguistic terms such as ACCEPTABLE, SOMEWHAT ACCEPTABLE and UNACCEPTABLE.

In the classical logic (i.e. two-valued logic), the conditional statement "if...then" is represented by the syllogism of Modus Ponens, stated as follows:

(First Premise)	If A then B (the conditional)
(Second Premise)	A (the observation)
(Consequence)	B (the inference)

i.e. , $D = A \circ (A \rightarrow B)$ where "o" denotes the composition rule of inference.

It should be noted that in the classical structure of logic, the sets A and B are "crisp" sets and the observation A has to be an exact "crisp" A. In fuzzy logic, the syllogism of the Generalized Modus Ponens can be stated as follows:

$$\frac{\text{IF A THEN B}}{\frac{A'}{B'}}$$

The use of fuzzy, rather than crisp, sets provides a flexible advantage over the classical logic. Moreover, since the observation A is not exactly A but some fuzzy approximation to A, inferences can still be made even if the exact duplicate of A stated in the conditional hypothesis "If ...Then: is not observed. These advantages were somewhat overshadowed by difficulties encountered during earlier stages of development. However, more recent literature on fuzzy inference has dealt with these problems from a theoretical standpoint.

In dealing with risks associated with the transport of dangerous goods, the inference structure can be expressed in a fuzzy decision table as follows:

RISK POLICY PERCEPTION		PERCEIVED OCCURRENCE OF ACCIDENTS	
		B(1) INFREQUENT	B(2) FREQUENT
Perceived Costs of Accidents	A (1) Small	C(1,1) Acceptable	C(1,2) Somewhat Acceptable
	A (2) Big	C(2,1) Somewhat Acceptable	C(1,2) Unacceptable

More generally such rules may be stated as:

If A(m) and (or) B(n) then C(m,n);

Where:

A(m), B(n), and C(m,n), $m = 1, \dots, M$, $n = 1, \dots, N$, are "fuzzy linguistic" descriptors that are linked by the "linguistic connectives", "AND", "OR", and the conditional "If ... then".

In the decision table, the rows of the table have been defined as "the perceived costs of accidents" and represent the A dimension of the problem. The columns are defined as "the perceived occurrence of accidents: and represent the B dimension. These dimensions can be combined using fuzzy set calculus to obtain a representation of the interaction between the severity of costs of accidents and the occurrence of accidents.

For observed values of A and B and observed values of the representation of the interaction between A and B, one can select a rule for conditional statements which defines a conditional state close to the observed state. If the observed state is equally close to several state space representations, all of the decision rules can be combined to develop a single conditional rule.

3.3 DATA REQUIREMENTS

Perception Survey Description

One of the most critical factors in the application of fuzzy set methodology is the collection of meaningful data on public and "expert" perceptions of the membership of different quantitative measures within the domain of a linguistic variable.

As part of the research, a survey methodology was set up to acquire attitudes with respect to:

- o the severity of costs incurred as a result of accidents occurring from the transportation of dangerous goods in a specified area by a specified transportation mode;
- o the occurrence rate (likelihoods) of such accidents;
- o the acceptability of risks associated with such accidents.

The determination of attitudes on severities, likelihoods and risks was accomplished by having the respondent assign fuzzy measure values in the range (0, 1) and on a line segment (scale) for descriptive but fuzzy linguistic variables such as BIG and SMALL severity of costs, FREQUENT and INFREQUENT occurrence rate of accidents, and ACCEPTABLE, SOMEWHAT ACCEPTABLE and UNACCEPTABLE RISKS.

The survey questionnaire designed to illicit the above information included the following components:

- o a statement of the scenario that delimited the boundaries of concern, however loosely these may be defined;
- o an explanation of the line segment (scale), the meaning of the end points and a market on a scale;
- o a training section to illustrate possible correct responses;
- o data collection.

The last two components were repeated in order to specifically address accident severity, accident frequency and acceptability of accident risks.

In the survey, accident severity was measured in terms of BIG and SMALL costs using the following seven values on the cost dimension:

\$1,000	\$10,000	\$100,000	\$250,000
\$1,000,000	\$5,000,000	\$25,000,000	

The likelihoods were measured in terms of INFREQUENT and FREQUENT accidents for the following seven values on the frequency dimension:

1 per 100 years,	1 per 40 years,	1 per 20 years
1 per 10 years,	1 per 5 years,	1 per 2 years, 1 per year.

Based on the above severity and frequency measures, for each of the four quadrants of the linguistic variable combinations - (SMALL, INFREQUENT); (SMALL, FREQUENT); (BIG INFREQUENT); and (BIG FREQUENT) - there will be forty-nine joint values of costs and accident rates. In order to minimize the number of questions per subject, but at the same time attempt to avoid inconsistent responses, a 7 x 7 Latin Squares Design was used.

The 7x7 Latin Squares Design Model is given as follows:

ACCIDENT COST (\$)	AVERAGE YEARS BETWEEN OCCURRENCES						
	100	40	20	10	5	2	1
1,000	A	B	C	D	E	F	G
10,000	B	C	D	E	F	G	A
100,000	C	D	E	F	G	A	B
250,000	D	E	F	G	A	B	C
1,000,000	E	F	G	A	B	C	D
5,000,000	F	G	A	B	C	D	E
25,000,000	G	A	B	C	D	E	F

Where: A,B,C,D,E,F,G represent responses of 7 different subjects. Thus, there are 7 responses per subject per quadrant of linguistic variable combinations.

Data Collection

Three residential areas near North Toronto CP rail corridor were selected for data collection purposes:

1. The area located to the east of Mt. Pleasant Road to the south of Inglewood Drive to the west of the municipality boundary and to the north of Rosedale Parks;
2. The area located to the east of Avenue Road to the south of Walker Avenue, to the west of Yonge Street and to the north of Roxborough Street West;

3. The area located to the east of Bathurst Street, to the south of Davenport Road, to the west of Walmer Road and to the north of the railroad tracks.

A group of graduate students, all familiar with fuzzy set theory conducted a door-to-door survey of a randomly selected sample of houses in the area.

Apart from the public, survey data was also collected from planners from the City Hall, faculty members from the University of Toronto, Joint program staff and IBI Group staff. These data were identified as the "expert" sample for the perception survey.

Screening of Data

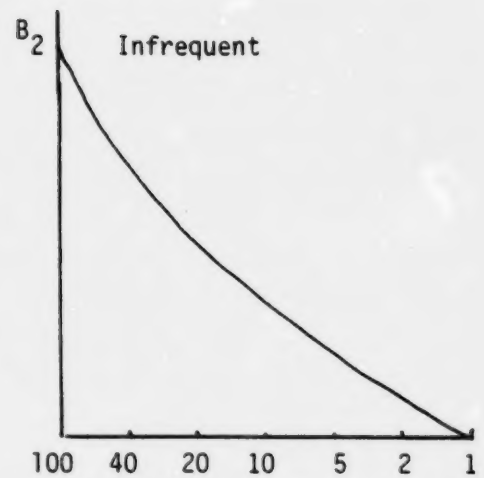
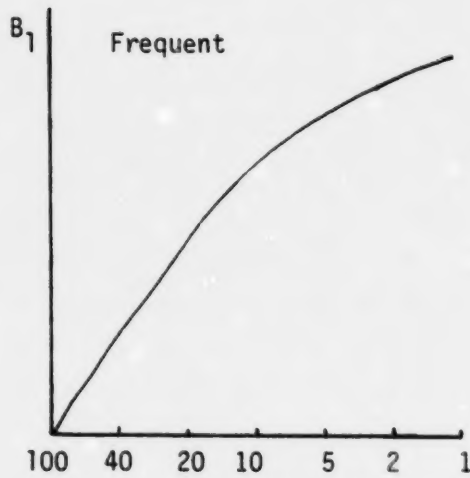
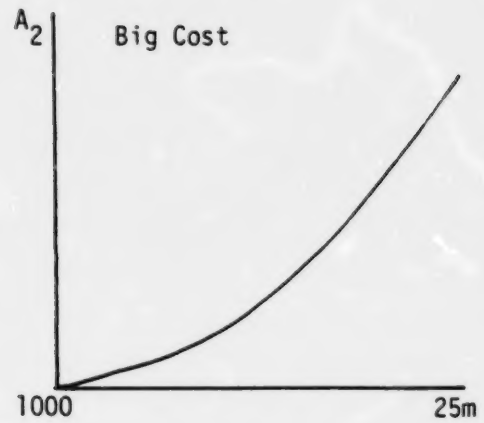
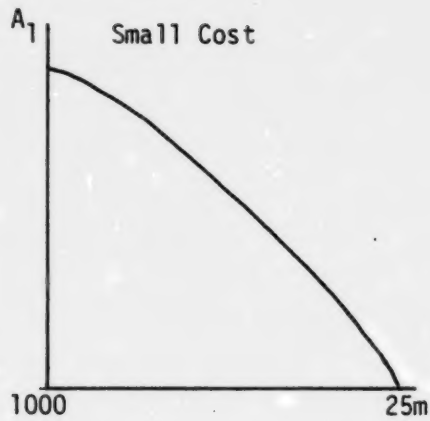
First, questionnaires were screened in order to exclude extreme or militant responses; i.e. people who believe that all accidents are very costly and very frequent and are not acceptable at all. In Part-A, (i.e. accident severity) and in Part-B, (i.e. accident frequency), about 6% of the responses were labelled extreme or militant but the corresponding figure was about 23% for Part-C (i.e. acceptability).

Next the data were checked for internal consistency. The expected response (membership) curves should appear as shown in Exhibit 3.1.

If the observed plotted curve appeared similar to the expected curve, then the associated data were classified as "good"; otherwise the data were not included in the remainder of the analysis. More specifically if at least 2 points of the curve were out of place or the curve was descending whereas it should have been ascending and vice versa, then the data were considered inconsistent and therefore rejected.

For Part-C (the acceptability of accidents) the method that determines the "goodness" of data was somewhat more complicated. This is due to the fact that the acceptability of an accident is dependent on the interaction of the severity of an accident and its likelihood.

Exhibit 3.1
Expected Membership Curves



It is clear that for fixed values of accident frequency if accident severity is increased, then the membership values should decrease for the linguistic variable "ACCEPTABLE". Similarly for fixed values of accident severity, if accident frequency increases, membership values should again decrease for the linguistic variable "ACCEPTABLE".

The survey results were generally consistent with the above relationships; however, there were fluctuations due to individual errors and limited data points in the sample. A procedure was developed to smooth the survey response data in order to overcome inconsistent patterns in the responses. The procedure involved the computation of average responses across each value of accident severity and each value of accident frequency. The average values were recombined to generate an average response surface. The surface was then normalized to ensure that at least one value was set at 1 and one at 0.

Survey Results

After data collection, screening and necessary computations outlined in the previous section, resulting membership curves were plotted for each linguistic variable considered in this study.

The membership curves for the perceived severity of costs to the community are shown in Exhibit 3.2. As shown in the exhibit for both "SMALL" and "BIG" (LARGE) cost, public and expert perceptions are similar. However, there are points at which the average expert-perception dominates the average public-perception for the "SMALL" costs. The opposite is true for the "BIG" (LARGE) costs. However, these are not appreciable.

The membership of the likelihoods of accident occurrence rates are shown in Exhibit 3.3. This time there is a more pronounced difference between the public perception and the expert perception and in this case the dominance is total. The average expert perception dominates the average public perception for the "INFREQUENT" accident likelihoods, while for the "FREQUENT" accident likelihoods the average public perception dominates the average expert perception.

Exhibit 3.2
MEMBERSHIP CURVES - SEVERITY OF COSTS

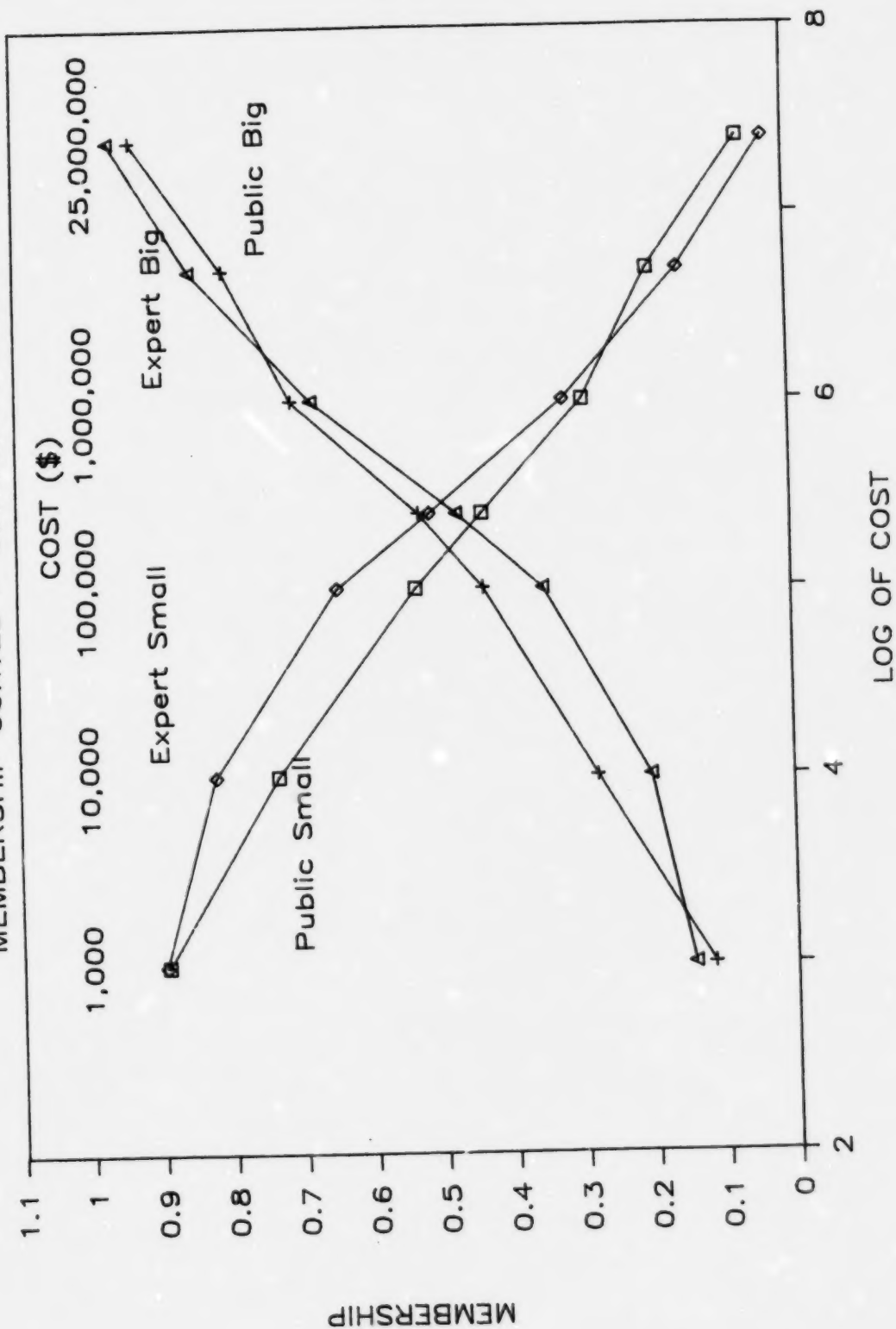
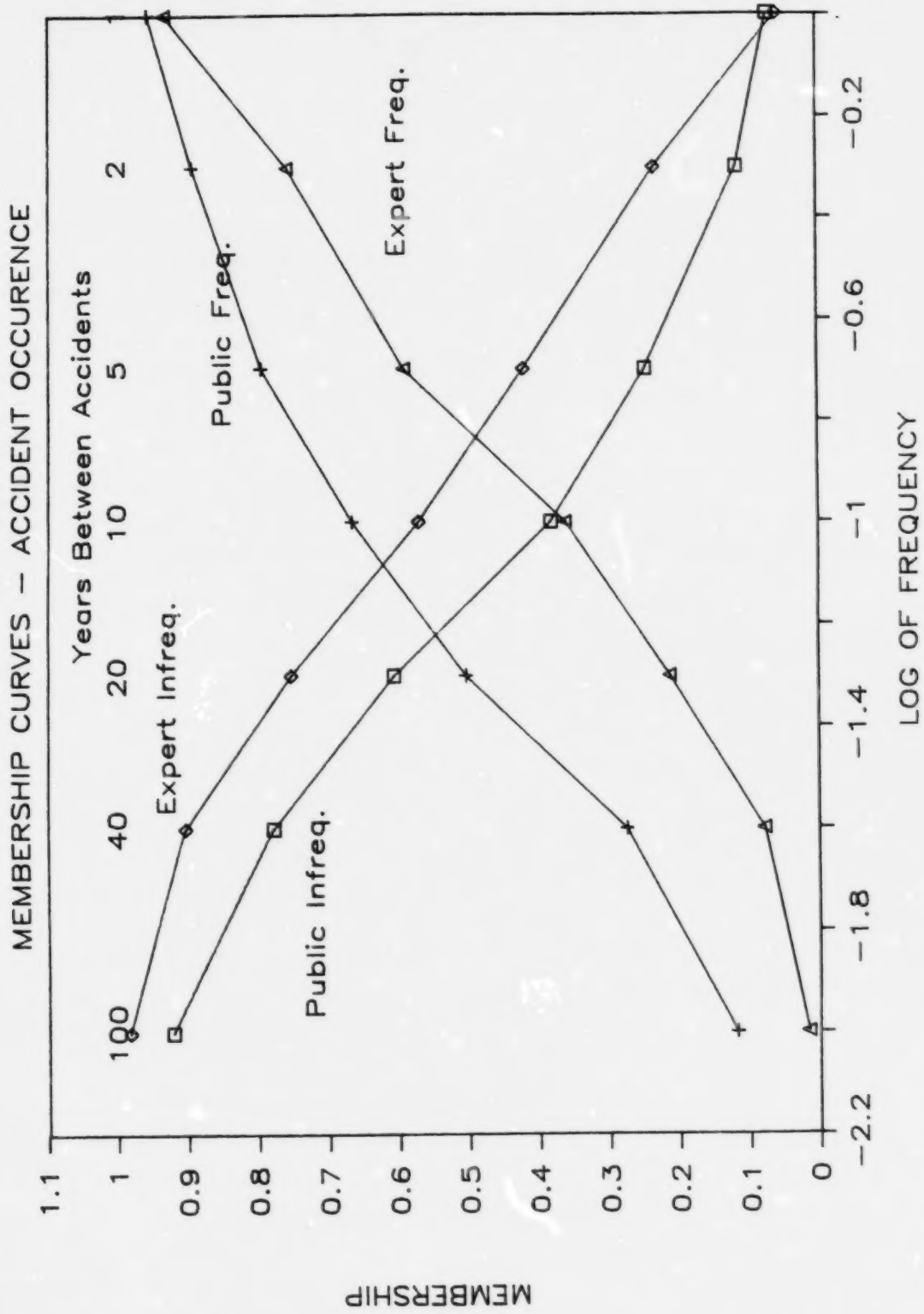


Exhibit 3.3



From these two sets of graphs, i.e. the severity of costs and the likelihood of accidents, a trend is apparent that will become much more pronounced later. The experts tend to be more tolerant of minor accidents and less tolerant of major accidents than the public. In other words, expert perception classifies a cost magnitude with a greater membership value into SMALL costs than the public perception, but the experts classify the same cost magnitude with less membership into "BIG" costs than the public.

Similarly, the expert perception classifies a given likelihood magnitude with greater membership into "INFREQUENT" with less membership in the "FREQUENT". A similar trend was observed in the acceptability dimension. That is the expert perception appears to be more tolerant to minor accidents and less tolerant to the major accidents than the public.

Risk Perception Models

The survey results outlined in the previous section provide an example of an inference structure that could be used for the analysis of alternative transportation scenarios. The parameters determined through the survey, after appropriate smoothing, identify a specific model for the analysis of future circumstances.

By obtaining two sets of data one from the public and the other from experts, two sets of parameters can be determined and hence two specific models for risk perception can be identified: "public perception" and "expert perception". In order to display the usefulness of these models in assessing future scenarios, we have hypothesized two states:

- o System State 1 (Catastrophic): Catastrophic but rare accidents (i.e. accidents that may be associated with "BIG" costs and "INFREQUENT" occurrences).
- o System State 2 (Chronic): Minor but often occurring accidents (i.e. accidents that may be associated with "SMALL" costs and "FREQUENT" occurrences).

In terms of membership values these were defined as follows:

Observation 1: (Catastrophic)

A* = 0.00 0.00 0.00 0.20 0.50 0.70 1.00 (BIG Cost)

B* = 1.00 0.70 0.60 0.00 0.00 0.00 0.00 (INFREQUENT)

Observation 2: (Chronic)

A* = 1.00 0.90 0.30 0.00 0.00 0.00 0.00 (SMALL Cost)

B* = 0.00 0.00 0.00 0.20 0.60 0.90 1.00 (FREQUENT)

Based on the parameters of the model obtained from the survey results, the public risk perception and the expert risk perception associated with the two hypothetical states can be analyzed. The results on the acceptability dimension are as follows:

RISK PERCEPTION	OBSERVATION 1 (Catastrophic)	OBSERVATION 2 (Chronic)
Public	(0.30,0.62)	(0.25,0.63)
Expert	(0.44,0.47)	(0.51,0.51)

These represent the compatibility (i.e. membership) of public and expert perception with the linguistic concept "SOMEWHAT ACCEPTABLE". For this concept a membership closer to 1 implies greater acceptability. The above figures indicate that the expert perception is more lenient (more tolerant), at least in terms of greater values for the lower bounds. At the same time, the expert perception appears to be more specific and more precise than the public perception of risk which has a larger spread. Recall that Observation 1 is a hypothetical, catastrophic but rare event whereas Observation 2 is a minor event that occurs more frequently. From the above table, we see that public's risk perception of the two types of events is fairly similar, i.e. from (0.30, 0.62) to (0.25, 0.63). However,

the experts; risk perception separates these two events more clearly, by classifying the "catastrophic but rare event" with a lower and therefore less acceptable gradation (0.44, 0.47), and by classifying "the minor frequent event" with a higher gradation (0.51).

3.4 AN ASSESSMENT OF THE FUZZY-SET APPROACH

Some of the more serious problems encountered in the application of fuzzy sets in this study concern the experimental survey. This effort was intended to be a pilot survey, and some of the problems could be overcome by improving the survey design. For future reference, however, it is useful to draw on this project's experience.

A number of shortcomings in the design of the questionnaire were identified through its application. These included:

- o the questionnaire was tedious to complete due to the repetitive nature of both the training sessions and actual questions;
- o the term "cost to community" used in the questionnaire was thought to be ambiguous and the definition of accident severity in terms of dollars alone was thought to be restrictive;
- o the questionnaire did not explicitly reference the benefits derived by a community from the transportation of dangerous goods. Therefore, a common baseline was not established against which the cost of accidents could be measures.

A review of possible alternative definitions of accident severity is contained in Appendix B. The proposed definitions are multi-dimensional and would therefore reduce ambiguity at the cost of added complexity.

Other shortcomings were identified through the analysis of the survey results. Specifically, there were problems in obtaining consistent

data on the respondents' perceptions with respect to the acceptability of accidents. In the design of the questionnaire, a Latin Squares design was used to minimize the number of questions per subject, but at the same time avoid inconsistent responses. The data collected on acceptability of risks using this technique produced a trend that is generally consistent, i.e. accidents with low severity and low frequency of occurrence are judged to be more acceptable than accidents with high severity and high frequency of occurrence; however, there were fluctuations due to varying perceptions and limited data points in the sample.

The results indicate that a great deal of emphasis will need to be placed on data collection in any application of fuzzy set theory to the determination of public perceptions of the acceptability of risks associated with the transportation of dangerous goods. In addition, it appears that assigning membership values to two dimensional variables (eg. combinations of accident severity and accident frequency) is a difficult process and that a relatively large sample size is required in order to obtain consistent membership curves with respect to these variables. The addition of another dimension to the variable may yield even greater measurement problems that may not be possible to overcome in a cost-effective manner.

Other problems encountered in the course of the study are more generalizable. First, since very little research has been undertaken on public perceptions of the risk acceptability of the transportation of dangerous goods, there is no indication that these perceptions remain stable over time. It is likely that these perceptions are greatly affected by the most recent releases of hazardous goods since accidents of this type are relatively rare. As a result, the evaluation of alternative courses of action may be biased towards those solutions that address the most recent problems that have occurred. This, of course, is not a problem unique to the fuzzy set approach, but plagues most research based on "expressed perceptions".

Although linguistic variables can be used to characterize complex phenomenon, the complexity can make it difficult to select appropriate variables. In the sample application of the fuzzy set methodology, the severity of an accident was defined in terms of cost to community (big or small). This definition of accident severity was too vague. The respondents wanted a definition of the size of the community, indications of whether the costs included direct and indirect costs, and an indication of whether or not injuries and fatalities were to be included in the concept of "cost to community". Any vagueness in the definition of quantitative variables that are transformed to linguistic variables will compound the problem of estimating fuzzy sets.

With respect to the acceptability of different combinations of accident severity and frequency, several respondents indicated that any combination would be unacceptable. This may have resulted from the lack of an explicit statement on the benefits which accrue to society from the transportation of dangerous goods.

One of the strengths of fuzzy set analysis is that information on the public's perception of trade-offs between different variables can be gathered. One of the difficulties with the technique is the effort required to develop an effective and efficient survey protocol to measure these perceptions. In addition, although the technique is useful in analyzing simple trade-offs, it is not clear if this analysis could be extended to analyzing the trade-offs between alternatives that can not be defined by single point variables. For example, fuzzy set analysis could be used to measure the acceptability of risks associated with accidents of high severity but low frequency of occurrence versus accidents of moderate severity with a higher frequency of occurrence. However, it is more difficult to measure differences in the acceptability of perceived risks of alternatives that have the same expected values for accident severity and frequency but different joint probability distributions for these variables.

In general, fuzzy set analysis cannot be viewed as an overall replacement for probabilistic analysis in risk assessment; however, it provides a means for including public and expert perceptions and attitudes within the evaluation of alternatives. This could be accomplished as suggested in the research paper through the development of a linguistic based "inference engine". The acceptability of various alternatives could be measured based on expected characteristics of these alternatives as long as these characteristics (eg. accident severity and frequency) were elements of the inference structure.

Fuzzy set analysis can provide a direct measure of public perception with respect to the acceptability of various risks associated with the transportation of dangerous goods. In particular, information can be obtained on how the public and experts view the trade-offs between two variables such as accident severity and frequency. Data on the perceptions of the acceptability of relatively rare events can be obtained through surveys even though the events of interest have not occurred in the recent past by presenting various scenarios to those being surveyed. In other words, fuzzy set analysis is not constrained by data availability to the same way as probabilistic analysis of rare events.

Overall, one can conclude that fuzzy set analysis may facilitate the inclusion of public perceptions of risk acceptability in the evaluation of alternative methods for the transportation of dangerous goods. As was the case with probabilistic analysis, the effectiveness of an evaluation of alternative courses of action can be improved if fuzzy set analysis is not used on a stand-alone basis to rank alternatives. However, in the absence of other data the analysis can be used alone to shed some light on the perceived trade-offs between alternatives. Furthermore, the application of fuzzy set analysis requires considerable effort in the development and implementation of a survey protocol if useful information is to be obtained.

4. DEVELOPMENT OF AN EVALUATION FRAMEWORK

4.1 INTRODUCTION

Over the past few decades, industrial development and technological innovation have increased the production, distribution and utilization of dangerous commodities. Several recent accidents, resulting in the release of dangerous goods during transport have increased public awareness of the potential risks associated with the movement of hazardous substances. The transportation of dangerous goods by rail has attracted considerable attention because of the large volumes transported and the routing of rail lines through major population centres. The 1979 derailment of a Canadian Pacific freight train in Mississauga, resulted in explosions, fires and the leakage of some eighty tons of chlorine. The subsequent evacuation of about 225,000 residents and the resulting economic losses, estimated at \$68.7 million, attest to the potential catastrophic consequences associated with the movement of dangerous commodities through urban areas.

The problem is one of providing for the efficient movement of dangerous commodities while keeping the risks associated with their transportation at an acceptable level. At present, significant quantities of dangerous goods are being transported by rail through some of the most densely populated urban areas in Canada. In the event of an accident resulting in the release of one or more hazardous substances, the lives of hundreds of people could conceivably be placed in jeopardy.

4.2 ALTERNATIVE TRANSPORT STRATEGIES

The search for alternative methods and/or means of transporting dangerous goods must focus on reducing the risks to some "acceptable" level while working within some cost and operational constraints. The risks associated with the transportation of dangerous goods can be reduced by

lowering the probability of any, or all, of the three major components of risk:

1. The probability of an accident involving vehicles transporting dangerous goods.
2. The probability of a release of dangerous goods if an accident should occur during their transport.
3. The possible consequences associated with the release of a dangerous commodity during transportation.

Another approach may be to improve public perception of the risks associated with the transportation of dangerous commodities through increased information dissemination and public debate on the issue of risks to the general public. Although this would have no effect on the absolute risks associated with the movement of dangerous commodities, it might increase public understanding and acceptability of those risks on which they may have a distorted perception of as a result of sensationalistic journalism, or pressure from special interest groups.

Alternative dangerous goods transport strategies may be broadly classified into six generic categories:

- o reduction of volumes transported;
- o improved operating procedures;
- o improved equipment safety;
- o infrastructure improvements;
- o rerouting;
- o modal diversions/redistribution.

Reduction of Volumes Transported

This alternative is often overlooked and yet may be the best long term solution for some dangerous commodity movements. In the short term, the use of some form of hazardous goods transport tax could be imposed in an attempt to reduce the volume of dangerous goods movements. The effectiveness of these measures will depend on the price sensitivity of demand for transporting dangerous goods. Given that most dangerous goods are essential industrial commodities, however, increased transport costs are not likely to affect total volumes. Nevertheless, revenue generated through the special tax could be used for more effective risk management, or infrastructural and operational improvements to reduce risks associated with the movement of dangerous goods.

Another alternative is to implement zoning by-laws to restrict the movement of dangerous goods through certain areas. Such measures are not likely to result in any significant reduction in volumes being transported, but may force certain flows to be rerouted. A differential dangerous goods transport tax system (i.e. higher taxes on certain routes than others) may have the same effect.

In general, measures such as taxes and zoning by-laws would probably have only a marginal effect on the volumes transported and hence result in a small reduction in the probability of an accident involving dangerous goods. Given the rate event probabilities at present, it is not likely that the resulting benefits (i.e. lower levels of risk) could be quantified in any meaningful way.

Improved Operating Procedures

The operating procedures of vehicles transporting dangerous goods are strictly regulated in Canada. Tighter regulation, in the form of more frequent and comprehensive vehicle inspection and maintenance, more restrictive speed limits, and limitations on the size and design of vehicles

engaged in the transportation of dangerous commodities have been advocated. Other possible changes to the operating procedures include restricted hours of operation, specific regulations as to the number and types of dangerous commodities transported together, and mode specific options such as unit trains or road convoys.

Improved Equipment Safety

The safety standards for equipment used to transport dangerous goods have received considerable attention in recent years. Emphasis has been placed on strengthening the container against puncture, crushing, and fire in the event of an accident. Another area of interest has been the fill and safety valve systems employed on pressurized tanks used to transport dangerous liquids and gases. Vehicle design improvements focusing on reducing equipment failures are also being investigated. With reference to the transportation of dangerous commodities by rail, recent amendments to the regulations aimed at improving equipment safety include more widespread use of tank head puncture resistance systems, double-shelf couplers, thermal protection systems, and a change-over to roller bearings. Further improvements in the area of equipment safety can be achieved, but given the safety standards now in effect the cost of incremental improvements may prove to be excessive with respect to the potential benefits of these improvements.

Infrastructure Improvements

Infrastructure improvements need to be addressed on a mode specific basis. In the case of rail transport, the removal of at-grade crossings, strengthening of the track bed and ties, and the replacement of jointed rails with continuous welded rails would improve the infrastructure quality. Other improvements worth investigating include more frequent hot box and dragging equipment detectors, and improved signalling and early warning systems. In heavily populated urban areas the use of more underground or elevated pedestrian walkways in conjunction with improved fencing

and tighter security could reduce the number of accidents involving trespassers and accidents resulting from vandalism.

In contrast to the rail network which is a private right-of-way, the road network is a public right-of-way serving a wide variety of users. This makes the identification of specific infrastructure improvements difficult when assessing the risk of transporting dangerous goods over the road. One approach may be to specify dangerous goods routes on the basis of geometric design standards, traffic volumes, roadside hazards and obstructions, shoulder and median widths, etc. Specific route segments could then be analyzed to identify specific problem locations (i.e. sharp curves, steep inclines, restricted visibility, roadside hazards, steep embankments) requiring improvement.

Rerouting

The option of rerouting the flow of dangerous goods utilizing the same mode is often considered when the mode of transport is perceived to be relatively safe but the risks associated with the movement along the route are felt to be too high. Rerouting can be employed to avoid heavily populated areas or environmentally sensitive regions, thereby considerably reducing the possible consequences associated with the release of dangerous commodities during transport. The probability of an accident involving vehicles transporting dangerous goods may also be reduced by rerouting but this is generally not the primary consideration. In fact the probability of an accident may increase as a result of rerouting but the reduction in possible consequences could more than offsets the increase resulting in lower overall risk.

An increase in accident probability for a given movement could occur on a secondary route since the primary transportation routes often have the highest quality of infrastructure (eg. railway main lines, expressways), or are significantly shorter than secondary routes.

Modal Diversion/Redistribution

Modal diversion is an alternative when the risks associated with the transportation of hazardous goods are perceived to be more mode specific than route specific. Modal diversion generally implies a change in route as well as a change in mode, and as such, may be considered when rerouting options are limited or extremely costly. Evaluation of the risk associated with alternatives involving different modes of transport is very difficult because there is very little in common between the alternatives. This necessitates an independent analysis of each alternative and an evaluation framework to compare the acceptability of each option given the uncertainty surrounding the risk assessments.

Another alternative under the general category of modal diversion is the redistribution of dangerous commodity traffic. Generally dangerous commodities are transported in large quantities by rail over long distances and then transferred to road transport for distribution to their final destination. Part of the problem of dangerous goods rail movements in Canadian cities is that railway yards are located within the urban area. This forces dangerous goods traffic to be routed through the area and also leads to some unnecessary movement. An alternative to the present system may be to develop dangerous goods rail yards outside major urban centres. The through traffic could be rerouted around the city and the local traffic diverted to highway transport where the greater flexibility in routing could be used to minimize the possible consequences of an accidental release.

4.3 GENERAL CONCEPTS OF EVALUATION

The fundamental purpose of an evaluation framework should be to identify and illuminate for the "decision-maker" the basic trade-offs between the different alternatives and the degree to which they meet conflicting objectives that affect different groups. For some alternatives that differ only in terms of cost, such as the choice of equipment, the

evaluation may be a relatively simple comparison of the present values of life-cycle costs. At the other end of the spectrum are certain types of problems that have complexities that do not allow an evaluation in simple terms. The transportation of hazardous goods is one such type of problem, with the following complicating factors:

1. Multiple, conflicting and incommensurate objectives relating to costs, event probabilities and consequences.
2. Lack of data needed to accurately estimate both the event probabilities and consequences.
3. Conflicts between various groups, including transporters, the general public, and the specific people located along alternative routes.
4. People differ in their perceptions of the problem, eg. degree of risk, and attitudes towards accepting these risks.

Since an evaluation should recognize and attempt to handle these issues, it is not surprising that an effective evaluation methodology has not been designed for comparing alternative hazardous goods transport policies. The purpose of the next section is not to present a comprehensive framework for such an evaluation, but to provide some guidelines for the development of such a framework.

4.4 GUIDELINES FOR AN EVALUATION FRAMEWORK

As may be evident from the wide range of alternatives discussed in the previous section, an effective risk management (or reduction) strategy may include different components dealing with various aspects of the system. Certain measures, such as a special transport tax or zoning by-laws, are aimed at regulating demand (or flow of dangerous goods). Others are technical or technological in nature dealing with improved operations, rolling stock or infrastructure. These are aimed at reducing accident or release probabilities. Rerouting or redistribution options, on the other

hand, may affect accident probabilities (e.g. diverting traffic to a route with better track conditions), but are primarily aimed at reducing accident consequences, or exposure to risk (e.g. diverting traffic to routes through less densely populated areas).

In order to appraise all of the possible alternatives and to combine the most cost-effective measures in a strategy to minimize risk (or at least achieve acceptable levels of risk), it is certainly desirable to adopt a comparative evaluation framework that can deal with the full range available options using a common set of criteria, or measures of effectiveness. In dealing with transportation of dangerous goods, however, the nature of the "rare event" environment and the related data problems, make it difficult if not impossible to tackle the evaluation problem in this comprehensive fashion.

The fundamental problem is that the impact of different measures aimed at reducing risk cannot be quantified in a manner that would facilitate a comparative evaluation. With the available data, there is little, if any, hope of establishing meaningful relationships between operational variables (e.g. volume, speed, equipment type, track conditions, etc.) and components of risk (i.e. event probabilities and consequences). Past studies have tried to establish such relationships. As argued earlier in this report, however, past studies trying to tackle the problem with detailed fault-tree analysis have been somewhat misguided, not realizing the full extent of the data problems and the limits of their own analytical tools.

In the case of demand management type measures (i.e. reduction of volumes), for example, the marginal changes in dangerous goods flows could possibly be quantified. However, it is the relationship between marginal changes in quantity and risk that is difficult to establish. At this stage, the evaluation has to rely on certain amount of "judgement". The problems are amplified when such demand management type measures have to be compared with, for example, options involving modal diversion. Consider an example involving two available options: to reduce the volume of dangerous

goods currently moving by rail, X , by X ; and to divert all of X to highways along the same route. Given the current state of data, this problem can never be tackled in a probabilistic way (using expected value analysis) to yield clear cut choices. At best, quantitative analysis could provide some broad ranges of estimates which may help the decision-maker, but still not eliminate the need to rely on value judgements or expert opinion.

In the case of technology options (both rolling stock and infrastructure) and other technical considerations concerning operations, traditional tools of risk analysis (i.e. probabilistic approach) have even less to offer in reaching decisions. The impact of marginal improvements on "risk" (or any of its basic components) cannot be addressed in a probabilistic manner, at least not with an acceptable degree of confidence that can be attached to the results. A thorough understanding of the system is, of course, essential to making informed decisions, and in this respect, detailed fault-tree analysis can prove to be useful, particularly in identifying "weak links" in the system. However, fault-tree analysis based on allegedly "objective" event probabilities (derived from historical data), cannot be relied upon as a decision tool.

The evaluation of technical or technological measures aimed at reducing risk levels cannot be freed from "expert opinion" or "engineering judgement". In this context the subjective probability approach may offer some potential, reducing the reliance on hard data and, facilitating the incorporation of expert opinion in the analysis as well as decision making. The use of subjective probabilistic estimates in risk assessment is reviewed in Appendix C. The analysis of expert opinion could also be approached using fuzzy set theory. A fuzzy inference structure may also prove to be potentially useful in reaching decisions based on expert opinion.

In evaluating rerouting or redistribution options, similar problems may arise. Since the relationship between operational parameters and risk (or its components) cannot be established, a probabilistic evaluation of alternatives would run into the same problems alluded to above. In

the case of rerouting or redistribution options, however, the overriding consideration is often exposure to risk (or consequences given an accident and a release). Thus, the evaluation can concentrate on this aspect instead of attempting a probabilistic treatment of expected accidents, releases or damages. The following example provides an illustration of how this can be accomplished in a somewhat qualitative manner (emphasizing "exposure") but avoiding undue reliance on event probabilities.

4.5 EXAMPLE, EVALUATION OF RAIL REROUTING ALTERNATIVES

This example is presented to illustrate the basic approach of the proposed evaluation methodology; the definition of alternatives is general and the numbers used are fictitious. Three alternative rail routes for the transport of liquid hazardous goods are being evaluated, including the currently used (status quo) route. All liquid hazardous goods are being considered as a group. The measures used for comparison in this case are:

1. Cost: annual transport costs of hazardous goods.
2. Event probabilities: annual probability of an accident resulting in a release.
3. Potential consequences:
 - (1) population living within a 250 m radius of an accident site;
 - (2) population living within a 250 m to 1,000 m annulus of an accident site.
4. General population exposed to risk:
 - (1) total population living within 250 m of the rail line;
 - (2) total population living within 250 m to 1,000 m of the rail line.

Exhibit 4.1 summarizes the information for the three routing alternatives. The cost estimate for routes 2 and 3 are expressed as additional annual costs relative to the present route (route #1). The event

EXHIBIT 4.1

DATA FOR EXAMPLE 1

MEASURE	REROUTING ALTERNATIVES		
	ROUTE #1 (Present Route)	ROUTE #2	ROUTE #3
Cost of Implementation (Additional Annual Cost \$10 ⁶ /yr.)	-	3	7
Event Probabilities (Annual Probability of Accident resulting in a Release)	10 ⁻⁴ to 10 ⁻³	10 ⁻⁴ to 10 ⁻³	10 ⁻⁴ to 10 ⁻³
Potential Consequences			
- population within 250 m of accident site	900 - 1,100	600 - 850	400 - 600
- population within 250 m to 1,000 m of accident site	18,000 - 21,000	15,000 - 17,000	4,000 - 7,500
Total Population Exposed to Risk			
- within 250 m of rail line	100,000	75,000	60,000
- 250m to 1,000m of rail line	300,000	250,000	90,000

probabilities are presented in terms of the 90% confidence interval limits on the estimate. In this example, the confidence bounds are constant across alternatives, as infrastructure, equipment, and operating procedures were assumed similar for the three routes. In order to highlight the variability in the level of possible consequences for the three alternatives, two measures of risk exposure are used: population exposed to an accident release of a hazardous commodity; and the total population along each route exposed to the risk of a possible accident resulting in a release. Each measure of exposure was divided into two levels of risk: high risk (0-250 m); low risk (250-1,000 m).

In this example the alternative routes are more costly, but avoid the heavily populated areas and hence have lower potential consequences. A pair-wise comparison of alternatives can be done using a marginal-cost-to-reduced-risk exposure ratio. Comparing route #2 to route #1, the additional annual cost of \$3 million is offset by a reduction of 75,000 in the number of people potentially at risk (25,000 from the high risk area, and 50,000 from the low risk). From this information, which captures the fundamental trade-off involved in choosing between these routes, a cost-effectiveness ratio can be calculated. In this example, the ratio is calculated as the increased annual cost divided by the decreased population at risk and yields a figure of \$40 per year per person saved from risk. Comparing route #3 to route #1, this ratio is \$28 per year per person. Route #3 versus route #2 yields an incremental cost to exposure-reduction ratio of \$23 per year per person.

Though crude, the cost to exposure reduction ratios give the decision-maker a feeling of the trade-offs, and they can be compared with an estimated willingness to pay to avoid these risks. If, for example, it is felt that society as a whole, or even just the 75,000 people at risk, would be willing to pay \$40 per year to eliminate this risk then route #2 is better than route #1. This, of course, would require a judgement by the decision-maker based in part on the information prepared about the types of consequences from an accidental release. Consideration must also be given

to the relative distribution of people in the high risk and low risk zones. If, for example, the only effect on people in the low risk zone would be a requirement to stay indoors for a few hours during a clean-up, then the additional cost of route #3 over route #2 may not be worthwhile as 160,000 of the 175,000 people saved from risk are in the low risk zone. If a release would create major health problems in the high risk zone and minor health problems in the outer zone, then the additional cost associated with route #3 may be justified.

It should be noted that changing exposure to risk cannot be treated on a one-to-one basis by decision makers. The complaints of the 400,000 persons exposed on route #1 will seem small compared to the complaints of the 350,000 on route #2 not exposed to the risk but threatened with such a change. Those who live with risk for long periods of time are less vocal than those newly exposed or threatened with exposure.

The cost to exposure reduction ratios do not incorporate any event probabilities associated with an accidental release. A cost to expected consequence ratio can be constructed to give an indication of the expected number of people affected annually by hazardous goods releases. For routes #1 and #2 the expected number of persons affected annually are as follows:

	<u>Expected Number of Persons Affected Annually</u>	
	<u>High Risk Zone</u>	<u>Low Risk Zone</u>
Route #1	0.09 to 1.10	1.8 to 21
Route #2	0.06 to 0.85	1.5 to 17
Reduction 2 vs 1	0.03 to 0.25	0.3 to 4

The expected number of persons affected annually is indeed quite small, which highlights a major problem when trying to evaluate alternative dangerous goods transport policies. While the general population exposed

to the risks may be very large, the rare event probabilities are such that the expected numbers affected annually by dangerous goods releases are very small. In our example, the additional expenditure of \$3 million annually reduces the expected number of persons affected by 0.33 to 4.25. The cost to expected consequence ratio ranges from \$70,000 to \$9 million per expected person affected. Theoretically, this range could be compared with what society might be willing to pay to not have a person experience the consequences of a release, but practically, the range is too wide and the potential consequences too varied to demonstrate the best routing alternative. At best, this type of analysis will identify and illuminate the issues and trade-offs between alternatives. A judgement by the decision-maker is both necessary and appropriate.

The discussion has not addressed the political realities of the decision-making process within the public domain. In the above example, the residents along route #2 not exposed to risk at present, but threatened with the possibility if route #2 is selected, would undoubtedly generate significant public opposition. On the other hand, while the residents along route #1, currently exposed to risk, would support a proposed rerouting plan along route #2, opposition from route #2 residents can be expected to be much more organized and vocal. The decision-maker must anticipate this opposition and attempt to lessen its impact by keeping all affected parties informed throughout the evaluation.

4.6 CONCLUSIONS

The risks associated with the transportation of dangerous goods are characterized by very low event probabilities and very high potential consequences. The uncertainty and wide range of possible outcomes is clearly demonstrated when we attempt to focus on a specific transportation route and class of dangerous good, as evidenced in the preceding example. Objective probabilistic modelling for risk assessment cannot provide definitive statements about actual risks. Probabilistic analysis can only give an indication of the level of risk associated with the transportation of various types of hazardous commodities.

The uncertainty inherent in any assessment of the risks of transporting dangerous goods, combined with the wide range of possible alternatives has important implications for the development of an evaluation framework. The framework must focus on providing the decision-maker with the most complete picture possible of the alternatives. Though the specific evaluation may differ across different classes of alternatives (i.e. improved operating procedures, rerouting, modal diversion), in all cases the evaluation should:

1. Be sensitive to changes in costs, event probabilities and consequences.
2. Inform and illuminate the issues and trade-offs for the decision-maker who must ultimately use judgement to make a decision.
3. Be practical recognizing the limitations on available time, money and expertise.
4. Give results that are easily understood by the decision-making body.
5. Attempt to aggregate the impacts so as to decrease the dimensions confronting the decision-maker, without obscuring significant concerns.
6. Address the attitudes of groups affected.

The impacts associated with each alternative may be presented under five major categories.

1. Cost of Implementation
 - a) total financial costs
 - b) cost per tonne-km of hazardous goods shipped
2. Event Probabilities
 - a) probability of an accident
 - b) probability of a release given an accident

3. Potential Consequences

- a) number of injuries and deaths
- b) number of people relocated
- c) number of people affected by an accidental release

4. Risk Exposure

- a) population exposed to risk

5. Fuzzy Measure of Acceptability.

While the measures used for cost and event probabilities are relatively straight forward, though difficult to estimate, the definition of a measure of potential consequences is a particularly difficult aspect. For some very limited problems it may be possible to indicate these consequences through an estimate of injuries, deaths and/or number of people relocated. For most alternatives, however, these numbers will be elusive, being very dependent on factors such as the weather and topography at the particular time and location of an accident. Therefore, a reasonable surrogate measure for risk may be the population exposed to the risks associated with the transportation of the particular hazardous commodity. Some form of a fuzzy measure of acceptability is also desirable to aid the decision-maker in assessing the benefits of proposed alternatives. A qualitative assessment of the potential effects of an accident release should also be incorporated in the evaluation framework.

Given the rare event environment and the lack of an adequate data base to accurately estimate event probabilities and potential consequences, the use of a single (even best) estimate would be misleading about our degree of knowledge and could give poor evaluation results. The truth is that there is a range, e.g. the 90% confidence interval, for each estimate. The evaluation framework proposed here explicitly acknowledges this fact and advocates the use of these ranges.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 OVERALL STUDY FINDINGS

The stated objectives of the study were as follows:

- o To review on a theoretical basis the limitations of traditional objective probabilistic risk assessment methodologies and to determine if those limitations can be reduced;
- o to determine how one can use fuzzy set theory to improve probabilistic and/or subjective analysis of the risks associated with the transportation of dangerous goods.

As part of the second objective, guidelines for the evaluation of alternative transport strategies for the transportation of dangerous goods were developed. The overall findings of the study with respect to these objectives are summarized below.

Probabilistic Analysis

The major strengths of classical probabilistic analysis for the risk assessment of the transportation of dangerous goods derive from the comprehensive, systematic approach used and for those methodologies which use fault tree analysis, from the inherent flexibility offered by the detailed breakdown of the risks into discreet, identifiable event sequences. Estimation of the probabilities associated with each event that must occur to produce a system failure readily facilitates model sensitivity and alternative scenario testing.

The complex nature of traditional probabilistic analysis methodologies can also be sited as weaknesses of the models. These models typically require a considerable data base to be applied successfully. The

large data requirements, combined with limited data availability, necessitate numerous assumptions and value judgements. The complexity of the models not only obscures many of the assumptions, but make it very difficult to assess the cumulative effect of all the assumptions on the final model results. The general use of single point estimates of total risk is also a shortcoming of traditional models. Without some qualification attached to the final risk estimate, in the form of upper and lower bounds, the confidence in and usefulness of the estimates are diminished.

In this study, a probabilistic approach has been developed which recognizes the severe restrictions placed on risk assessments in a rare event environment by the lack of suitable data. The proposed methodology focuses not on a point estimate of risk, but on the specification of reasonable limits associated with the risks of transporting dangerous goods. This represents a major departure from traditional risk assessment models.

The proposed approach is not without its weaknesses. Problems arise in using the model if there are changes in "time" values of the probabilistic parameters due to changes in regulations governing the transportation of dangerous goods or in equipment design and operations. If there is reason to believe that the probability distributions are not static, it may not be possible to use all the historical data available on releases in order to estimate the parameters. The availability of data has a substantial impact on the "tightness" of the bounds on parameter estimates.

It has been clearly demonstrated that when we are dealing with rare events, the uncertainty of predictions based on the few occurrences of these events is generally of a high order. So much so, that definitive statements about actual risks are virtually impossible to state. In addition, objective probabilistic modelling does not resolve the problem of trade-offs between the risks associated with releases which have a low

probability of occurrence but high level of impacts and those with a higher probability of occurrence but a lower level of impacts.

Fuzzy Set Analysis

The research undertaken in this study involved the application of fuzzy set theory in the development of a knowledge based expert system that could deal with public perception towards the risks of transporting dangerous goods. The model can potentially provide a methodology for including public and expert perceptions in a structured manner within an evaluation process dealing with alternatives in this area. The expert system that was designed using linguistic rules is intended to capture trade-offs between accident severity and accident frequency.

The motivation for linguistic characterization is that they are less specific than numerical variables. Linguistic variables with the fuzzy set theory representation approximate characterization of phenomenon which are too complex or ill-defined to be described in precise terms.

One of the strengths of fuzzy set analysis is that information on the public's perception of trade-offs between different variables can be gathered. One of the difficulties with the technique is the effort required to develop an effective and efficient survey protocol to measure these perceptions. In addition, although the technique is useful in analyzing simple trade-offs, it is not clear if this analysis could be extended to analyzing the trade-offs between alternatives that cannot be defined by single point variables.

In general, fuzzy set analysis cannot be viewed as a replacement for probabilistic analysis in risk assessment; however, it provides a means for including public and expert perceptions and attitudes within the evaluation of alternatives. This could be accomplished through the development of a linguistic based inference structure. The acceptability of various alternatives could be measured based on expected characteristics of these

alternatives as long as these characteristics (eg. accident severity and frequency) were elements of the inference structure.

Fuzzy set analysis can provide a direct measure of public perception with respect to the acceptability of various risks associated with the transportation of dangerous goods. In particular, information can be obtained on how the public and experts view the trade-offs between two variables such as accident severity and frequency. Data on the perceptions of the acceptability of relatively rare events can be obtained through surveys even though the events of interest have not occurred in the recent past. In other words, fuzzy set analysis is not constrained by data availability in the same way as probabilistic analysis of rare events.

Overall, one can conclude that fuzzy set analysis may facilitate the inclusion of public perceptions of risk acceptability in the evaluation of alternative methods for the transportation of dangerous goods. As is the case with probabilistic analysis, this methodology cannot be used effectively on a stand-alone basis to rank alternative courses of action. Furthermore, the application of fuzzy set analysis requires considerable effort in the development and implementation of a survey protocol if useful information is to be obtained.

Evaluation Framework

Guidelines have been presented for the development of an evaluation framework to assess alternative transport strategies for the transportation of dangerous goods. The uncertainty inherent in any risk assessment in this area, combined with the wide range of possible alternatives indicates that the evaluation framework must focus on providing the decision maker with the most complete picture possible of the alternatives. The proposed guidelines for such an evaluation framework, which would apply across different classes of alternatives, are as follows:

1. Be sensitive to changes in all costs including infrastructure and operating costs, event probabilities and

consequences including accident costs, injuries, deaths and other impacts.

2. Inform and illuminate the issues and trade-offs for the decision-maker who must ultimately use judgement to make a decision.
3. Be practical recognizing the limitations on available time, money and expertise.
4. Give results that are easily understood by the decision-making body.
5. Attempt to aggregate the impacts so as to decrease the dimensions confronting the decision-maker, without obscuring significant concerns.
6. Address the attitudes of groups affected.

5.2 RECOMMENDATIONS

Based on the findings of this study, our recommendations with respect to probabilistic analysis, fuzzy set analysis and an evaluation framework for risk assessment in the transportation of dangerous goods are as follows:

Probabilistic Analysis

- o Future studies in the area of risk assessment with respect to the transportation of dangerous goods should be aware of the limitations of traditional probabilistic analysis techniques and the data available to apply those techniques. Specifically, there should be an awareness that the point estimates obtained from the application of traditional probabilistic methodologies are not meaningful in a rare event environment without some indication of the confidence bounds on those estimates. For example, if the expected risk of one approach for handling a particular dangerous goods movement were estimated to be lower than the expected risk of a second alternative approach, a decision-maker would tend to prefer the former. However, the estimated confidence bounds of the expected risks could overlap indicating that there is no statistical difference between the risks of the two alternatives;

- o the results of probabilistic analysis should not dictate policy with respect to the transportation of dangerous goods due to the uncertainties associated with this type of analysis. Rather, probabilistic analysis should be considered as an important component of an overall evaluation framework;
- o there is a need to develop probabilistic risk assessment models for the analysis of transportation of dangerous goods by truck and rail that could allow for comparisons of the structure of risk across the two modes. The models should account for the greater variability in road versus rail infrastructure, transport vehicles and operating conditions. The greater variability inherent in truck transportation can make it difficult for the decision maker to objectively compare rail and truck alternatives.

Fuzzy Set Analysis

- o Fuzzy set analysis is a promising tool for the assessment of attitudes and perceptions of the risks associated with the transportation of dangerous goods. The theoretical structure for such applications is in place, however, additional research is required on the development of appropriate survey protocols. These protocols should be able to measure perceptions with respect to multi-dimensional variables and attitudes on the trade-offs between variables;
- o the use of fuzzy set analysis in the development and application of subjective probabilities should be investigated. Fuzzy measures would make explicit the element of subjective vagueness in "expert judgement" processes.

Evaluation Framework

- o The guidelines for an evaluation framework presented in this report should be applied to the development of a comprehensive evaluation methodology. The methodology should stress the need to be pragmatic and should insure that the decision maker is aware of limitations of scientific approaches to the analysis of complex problems such as the transportation of dangerous goods.
- o In order to assist the decision-maker, there is a need to develop concepts to quantify the differences between alternative approaches to the transportation of dangerous goods. Possible concepts could include:

- development of ratios of accident consequences versus total operations cost;
- estimation of trade-offs between the resources invested in safety and the resulting reduction in risks and possible changes in operating productivity;
- description of alternatives in terms of confidence intervals for accident consequences versus frequency of occurrence rather than point estimates of the expected accident consequences.

Consideration should also be given to presenting these concepts in graphical form to allow for the presentation and assimilation of more information than possible through the use of numbers alone.

APPENDIX A

DATA REQUIREMENTS FOR PROBABILISTIC ANALYSIS

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DATA REQUIREMENTS FOR PROBABILISTIC ANALYSIS

REQUIREMENTS FOR PROPOSED MODEL

Both the probabilistic model developed in this study and other traditional risk assessment models use past data in order to estimate parameter values. As is the case with any statistical estimation technique, tighter confidence limits can be placed on the estimated parameters if additional data are used in the estimation. The need for additional data in order to narrow the confidence bounds on parameter values leads to two problems. First, given the rarity of events of interest such as releases of hazardous goods with very severe consequences there is often a lack of recent appropriate data. Since detailed information on the transportation of dangerous goods was generally not collected in the past, historical data that may be useful in the estimation process, are typically not available. Secondly, even when historical data are available, changing conditions with respect to transportation operations and equipment can reduce the value of the historical data.

Regardless of these limitations more complete basic data on the transportation of dangerous goods could potentially tighten the confidence bounds on statistical parameters. In addition, even under changing conditions, historical data could be used to check the performance and logic of fault tree and other analysis models developed to assess alternative future choices of action.

The types of data required for the proposed probabilistic model can be grouped into those related to the overall transportation of dangerous goods and those related to specific release incidents involving dangerous goods. The specific information that would prove useful are as follows:

- o volumes of dangerous goods carried by class of commodity by mode. This volume data would be most useful if expressed in terms of tonne kilometres;
- o for each mode, the proportion of volume carried on different classes of facility, eg. main line versus branch line for rail traffic and two lane versus multi-lane highways for road traffic;
- o the number of release incidents and their location, transportation infrastructure conditions, operating characteristics such as speed and accident conditions such as type of impact;
- o at each incident the types and quantities of dangerous goods released and the severity of the consequences caused by the release including injuries, fatalities and property damage;

REQUIREMENTS FOR GENERAL PROBABILISTIC ANALYSIS

The data requirements for a comprehensive analysis of dangerous goods movements for both rail and truck modes fall into two categories:

- o accident information;
- o traffic flow data.

Accident information is important in order to estimate the relationships between accident type, operating conditions, suspected cause, commodity type, response action and impact. The flow data is necessary order to allow for the assessment of accident probabilities and also to permit the monitoring of trends in magnitude and frequency of the transportation of dangerous goods.

RAILWAYS

The following provides a comprehensive list of the data base required for the analysis of the transportation of dangerous goods by rail.

Information required on accidents involving dangerous goods with and without a release is:

- o location of accident;
- o type of accident - collision, crossing, derailment, etc.;
- o type of car or container;
- o speed of train at the time of accident;
- o visibility and other weather conditions at time of accident;
- o cause of accident - crew error, equipment failure, etc.;
- o results of accident - fire, explosion, spill, etc.;
- o quantity and type of product carried and amount released;
- o population density within 100 metres and 1,000 metres of the accident;
- o impacts in terms of deaths, injuries, property damage, loss to the environment, costs to the railway;
- o response actions taken.

The accident characteristic data is necessary in order to estimate the relationship between accident type, operating conditions, probable cause, commodity type, response actions and the impact of the accident. Care must be taken when developing these relationships to ensure that the proper cause and effect relationship has been identified.

In order to be able to predict the probability of an accident involving dangerous goods occurring, and to allow the monitoring of dangerous goods flows the following information is required:

- o the number of kilometres of track;

- o car miles and ton miles (or carloads) of all products moved;
- o car miles and ton miles (or carloads) of hazardous goods moved by commodity codes;

It is preferable that the traffic flow data is made available by origin/destination pair, by railway track section and possibly by municipality in order to allow for a monitoring of trends in the size and patterns of flows at a disaggregate level. This information is also important in order to relate the number of accidents or incidents on a section of railway to the volume of flows.

TRUCKING

Data requirements for the analysis of trucking accidents are similar to that required for rail. Accident characteristic data including location, quantity and type of product carried, accident type and cause, road and weather conditions if appropriate, operating conditions of the truck and also the accident consequences in terms of deaths, injuries, property damage, etc. are all important.

It would be desirable to collect traffic flow data by commodity by section of highway in order to permit detailed analysis of trends in traffic flows and in order to relate accident occurrence to volume of flow. However, the costs of this level of data collection would be prohibitive and therefore truck traffic flow data may be limited to aggregate volumes. More detailed information on flows could be collected on a sample basis to meet specific requirements.

CURRENT DATA COLLECTION

Information on dangerous goods accidents/incidents and traffic flow data are currently collected by the two major railways, trucking companies and various government agencies. In the past the data base of

accident information has been collected by different government agencies depending on the mode of transportation. With the new Transportation of Dangerous Goods Act, which will be completely in place by the first of July, 1985, all modes of transport will be required to report accidents involving dangerous goods to Transport Canada. The new Act will also provide for the monitoring of dangerous goods accidents at all points of shipment including during loading and unloading that occurs on the shippers or consignees property.

The following section provides a description of the accident and flow data collected involving the rail mode by the railways, CTC and Transport Canada. Data sources for trucking flows and accidents, while less comprehensive than rail data, will be described.

Railway Accident Information

The railways are currently covered by the CTC Regulations for Transportation of Dangerous Commodities by Rail. Under the general regulations the railways are required to immediately notify the CTC if a car is found to be leaking, damaged or defective, while in the carrier's jurisdiction, in a manner that could potentially cause a fire, explosion, injury, loss or life or a threat to the public. If none of these conditions are in effect the railways are required to report accidents within six days of their occurrence to the CTC. Accidents are not reportable if there has been less than \$750 property damage unless personal injuries result or dangerous goods are involved (not necessarily a release).

After an accident has been reported by a railway the CTC may or may not send an inspector to the scene of the accident, depending on primarily its severity, and accessibility. If an accident has occurred involving a release, a CTC representative will stay at the scene of the accident for the duration of the clean up and will then file a report to their office.

The railway is then required to file a full accident report with the CTC. The following information is required from the railways with regard to an accident:

- o location - the name of the subdivision, the mileage or the yard name;
- o date and time;
- o type of accident - incident, derailment, collision;
- o the train number;
- o the date the CTC is informed of the accident;
- o the number of injuries/deaths;
- o the CTC person in attendance;
- o the personnel who reported the accident;
- o the industry involved if a private siding;
- o the number of loaded and empty cars on the train;
- o waybill information for each car - car number, whether loaded or empty, shipper, consignee, origin, destination, type of car, car specifications, date and results of safety valve tests and due date of next test, when the car built/converted, whether a special permit is involved, location of the leak on the car (if there is a release), whether the car is damaged, quantity of goods transported and lost, notice of any violation of regulations;
- o costs are sometimes reported which include damage to equipment and track, costs of diverting other trains and overtime for staff and the destroyed contents of cars.

The CTC is primarily interested in the safety aspects of the railway accidents and therefore they routinely follow up with the railway to find out what was the cause of the accident. The railways are often not sure at the time of the accident and it may require further investigation.

The railways also provide annual returns of summarized accident costs to the CTC which show property damage (material cost of replacement of track and rolling stock), labour required, clean up costs, loss of car contents, and rerouting costs. These costs are not in the public domain.

In the last year the CTC has begun inputting the information sent to them by the railways with regard to accidents involving dangerous commodities into a computer system. As of this date, accident information is available back to the beginning of January, 1982 on their system. This computer file may be accessed by many keys and is the first time that dangerous goods accidents have been amassed separately from all railway accidents.

Discussions with personnel from both railways revealed that they both use a basic accident form for their own internal reporting which includes some information not required by the CTC. This information is collected mainly from the train crew. Additional information not provided to CTC includes:

- o weather;
- o visibility;
- o speed of the train;
- o names of the crew members involved.

After the accident has occurred, the railways follow up the cause of the accident to decide whether it is a shipper's error, carelessness or train crew error. Also a detailed investigation will be made with regard to the cost of the accident, in terms of how much track is repaired or replaced, equipment repair or replacement costs, loss of shipment, clean up costs, revenue costs due to blocked lines and overtime of crew due to the accident. The railways confirmed that these dollar cost figures are confidential.

Under the new Transportation of Dangerous Goods Act, the railways will be required to submit a full report of a dangerous goods accident within 30 days to Transport Canada using the 'Dangerous Occurrence Report'. The format of this report is shown in Exhibit 2.3. This report covers much of the information required by the CTC, but also requires the railway to estimate the probable cause of the accident, the weather conditions at the time of the accident, an estimated value and area size of the property damage. The railways under this new Act will still be required to provide immediate notification to the CTC if a leak or potential hazard is identified. At this time the personnel from CTC could not confirm whether the new Act would mean cessation of the railways filing dangerous accident reports to their agency. The information collected by Transport Canada will be made available to the CTC.

Missing on the Dangerous Occurrence Report is a good estimate of the total dollar costs of the impact of the accident but in most serious accident cases Transport Canada will conduct an investigation into the accident which will include these costs.

The new Dangerous Goods Act also includes a method for handlers of dangerous goods to report any incidents that they feel should be reported. The "Dangerous Goods Incident Report" is voluntary and is aimed at preventing accidents through the identification of potentially hazardous situations.

Railway Traffic Flows

The railways currently keep very detailed operating statistics with regard to the traffic flows on their system. Most of their information is gathered from the waybills. Relevant information to this study on the waybills are commodity type, number of carloads, gross ton miles of movement, origin and destination and the route of the movement. Transport Canada receives detailed information (origin/destination movements by city) from CN and CP regarding their traffic flows. These flows are then summarized using the nine commodity codes for dangerous commodities to provide

information on carloads and gross ton miles on a province to province basis and also on a through-province basis. Although the information received from the railways is more detailed than this, Transport Canada is permitted to only produce summary information in order to protect the confidentiality of the railway's clients. Transport Canada publishes this information about every three years in a report called The Transport of Dangerous Goods by Rail in Canada.

When a request is made to Transport Canada for more detailed information such as flows through a municipality they often suggest that the railways be contacted directly. If the railways are willing to provide the information they will most likely charge for this service since it is fairly costly to access their data base and summarize the required information.

Truck Accident Information

When there is an accident on the highways, whether or not it involves dangerous goods or not, the the provincial transportation authorities are notified immediately, either by their staff on the highway or by the municipal or Provincial police. The immediacy of the notification is dependent on the quantity of the release of dangerous goods and whether or not there is a threat to environment or property. The provincial transportation authority then notifies the appropriate agencies, either Public Safety or Environmental Branch where required.

A police accident report will be filed which contains all the pertinent information with regard to the accident including the weather, the state of the driver, the road conditions, the estimated damage to the vehicle, etc. This information is maintained in police files. The police are then required to make a report to the provincial authorities which includes information such as:

- o the location of the accident;
- o the people involved in the accident;

- o the quantity of goods and the estimated quantity of goods released;
- o where applicable, whether charges were laid.

The provincial authorities are responsible for estimating damages to the highway and the structures in the immediate area. The trucking company in their own report of the accident will have the final estimates of damage to the vehicles, quantity lost and compensation costs to the driver for any lost time or injury. These costs to the trucking company are kept confidential.

With the new Transportation of Dangerous Goods Act all accidents involving the trucking mode will be required to be reported to Transport Canada within 30 days on the "Dangerous Occurrence Report". The accident information required on the report form is the same as for the railways and the follow-up routine of investigating an accident will also occur for trucking accidents involving dangerous goods.

Truck Traffic Flows

There is currently very little detailed information available with regard to flows of commodities by truck. Each trucking company keeps track of their own flows using their waybills. Transport Canada is currently working closely with Statistics Canada to refine their For Hire Trucking Survey which is an annual sample survey of domestic intercity, for hire truck shipments. This data is currently not very reliable for the following reasons:

- o it does not include private companies;
- o no transborder shipments are included;
- o no intra-city movements are included;
- o only carriers earning over \$100,000 are surveyed;
- o limited sample size.

Transport Canada uses the information developed in the For-Hire Trucking Survey and publishes inter-provincial flows by commodity class showing tonnage and number of shipments in a report called The Transport of Dangerous Goods by Truck in Canada on a regular basis. Statistics Canada is currently preparing a For Hire Trucking Survey for the private trucking industry for future publication.

In the Province of Ontario roadside surveys of trucks have been carried out about every seven years in order to provide a profile of the current trucking and trends. In the last survey the nature and extent of dangerous goods movement were singled out as a specific objective of the survey. Origin/destination information is collected by commodity along with comprehensive information regarding the vehicle, type of carrier and other trip details. The report publishes inter-provincial flows (including trans-border flows) of dangerous commodities using a nine commodity classification. Dangerous commodities were shown to form approximately 8% of all truck movements and about 12% of all goods movements by tonnage.

RECOMMENDATIONS ON DATA COLLECTION

Rail

The data requirements for dangerous commodity transportation by rail include both comprehensive information regarding accidents and also detailed traffic flow data of dangerous commodities. Historical information on rail accidents involving dangerous commodities is available from the CTC in a computerized form back to 1982. In order to improve past records on dangerous goods accidents it would be advisable to extend this computerized data base as far back as the data quality permits. With the new Transportation of Dangerous Goods Act, Transport Canada will be the source for accident data in the future and if CTC regulations are retained this information will also be available from this latter agency.

The accident report forms required by the CTC and now by Transport Canada lack detailed information regarding the total costs and impacts of the accident which is important to the analysis of accident data. These costs/impacts include injuries, deaths, value of property damage, compensation, and costs to the railways. The railways currently calculate all of their costs including regard to cleanup, damage to track and equipment, staff overtime and rerouting costs but this information is kept private by the railways. Every effort should be made to have this included in the final accident report. Another area of information that is not shown on the new Transport Canada accident report form is the details of the response action taken as the result of a dangerous goods accident. By recording what steps were taken, the effectiveness of response can be analyzed.

Traffic flow data of dangerous goods is essential for accident analysis not only to put the accidents in perspective in terms of frequency of movements but also in order to better monitor trends in traffic flows by location. The traffic flow data currently maintained by Transport Canada gathered from the railways is only on a provincial level by commodity. This information is not very helpful when attempting to analyze dangerous commodity flows in high density areas. Therefore, although detailed flows are kept confidential by the railways and are also fairly expensive to develop, this information should at least be made available to Transport Canada for internal analysis and could possibly be made public with approval from the railways on a selected basis. Since disaggregate traffic flow data is currently not available it is very difficult to effectively and accurately analyze and model the risks of transporting dangerous goods by rail.

Finally, all of the information described above should be in a form that can be easily accessed and analyzed by the public through Transport Canada or another agency. Where the matter of confidentiality arises the railways should be consulted. The availability of good information in an easily accessible form will improve the quality of research on transportation of dangerous goods by rail.

Truck

Historical accident data for trucking accidents on the highway is distributed between the provincial government and police records. It would be beneficial to collect some basic information from these sources and develop an historical accident data base for the trucking industry. This would allow analysis of some trends in the trucking data but for details the provincial and police records could be accessed. As the Transportation of Dangerous Goods Act becomes effective, trucking accident data will be available through Transport Canada. As with the railway data it is important that good cost/impact data and response action information is included with the final accident report forms.

The data most lacking with regard to trucking of dangerous goods is accurate flow data. This may require an initiation of roadside surveys on major highways across the country on a regular basis (say every five years) in order that the accident data can be put into perspective and also to monitor flows in high density areas. The lack of detailed flow data at this time limits the quality and extent to which the risks associated with transporting dangerous goods by truck can be estimated.

As with the rail data it is important that the information regarding trucking of dangerous goods both accident data and flow information should be kept in a format that is easily accessible for research purposes.

APPENDIX B

DEFINITIONS OF ACCIDENT SEVERITY
FOR USE IN FUZZY SET ANALYSIS

APPENDIX B

DEFINITIONS OF ACCIDENT SEVERITY FOR USE IN FUZZY SET ANALYSIS MAJOR

LIMITATIONS OF A UNI-DIMENSIONAL VARIABLE

The lack of an appropriate measure for accident severity was identified as a major shortcoming of the trial application of fuzzy set analysis undertaken in this study. The use of a unidimensional variable such as cost to measure accident severity prohibited any explicit recognition of the perceptual trade-offs between different types of accident consequences.

The pilot survey experience suggested that the public does not necessarily perceive the consequences of a dangerous goods accident in terms of its total cost to the community at large. The total cost to the community represents too abstract a concept for the public to relate to in order to reveal their perceptions. A number of respondents to the survey explicitly indicated that the use of a unidimensional variable (i.e., total cost to community) for accident severity was inappropriate since they could not readily translate non-financial (or intangible) impacts into costs valued in monetary terms.

The possibility of using a more descriptive, multi-dimensional measure of accident severity was considered prior to the conduct of the pilot survey. However, the decision to adopt a single cost measure became necessary due to the limited scope of the pilot survey and the anticipated data collection problems associated with a multi-dimensional scale. It is now recognized that in order to overcome the difficulties encountered in the field, and later in the course of the analysis, future efforts should focus on a multi-dimensional definition of accident severity.

The multi-dimensional measure of accident severity could be assessed in combination with accident frequency in order to obtain percep-

tions of the acceptability/unacceptability of the specific risks associated with alternative means of transporting dangerous goods. This appendix presents both possible definitions for accident severity and indicates how these definitions could be combined with frequency measures in an attempt to develop a more complete picture of risk perceptions. It should be noted, however, that the concepts presented here are only meant to lay the foundations for future work and should not be viewed as an operational model for immediate survey applications.

BACKGROUND

In the traditional probabilistic approach to risk assessment, the simplest expression of "risk" is the product of the probability of release and the consequence of that release. As discussed in the chapter on probabilistic analysis, in a rare incident environment traditional risk models present serious, if not insurmountable, problems in deriving reliable estimates of release probabilities. Even if release probabilities could be estimated, probability distributions for the consequences of a given type of release are virtually impossible to determine in a rare incident environment.

Yet another problem in risk analysis stems from the fact that release incidents result in a wide variety of consequences and their combined impact is not always easy to assess. In the literature, accident consequences are often summarized using three major categories: injuries, deaths and property damage. The literature also suggests that single fatalities should be separated from multiple fatalities, and that another impact category be considered to include costs and inconveniences associated with the dislocation of affected residents. In some cases (e.g., with respect to radioactive material exposure), it is also suggested that temporal differences should be considered, and delayed health effects be taken into account.

Since most studies on risk assessment are ultimately concerned with policy or investment decisions, the tendency in the literature has

been to measure the aggregate impact of release consequences in terms of "expected value of damages." This, of course, raises the problem of attaching monetary values to human injuries and deaths, as well as to other intangible consequences such as pain, suffering and inconvenience. This subject has been covered in the economics literature, but the most fundamental problems facing the analyst in assigning monetary values to human life and intangibles still remain largely unresolved.

The problems associated with an "objective" approach to the assessment of release (or accident) consequences are then twofold. First, data that can be made available in a rare event environment does not permit the determination of probability distributions of release consequences. Second, the nature of the impacts is such that it is difficult to aggregate the cost of release consequences in a single measure. Due to these difficulties, an objective assessment of release consequences is rarely possible, and in cases where it is attempted, such analysis inevitably results in further controversy since the underlying assumptions always remain in doubt. Most decisions in this area must, therefore, be based on subjective considerations and often rely more on public perception than objective measurement.

Fuzzy set analysis provides a promising framework for measuring perceptions with respect to the severity of accidents (or release consequences). If appropriately structured, analysis can also be applied to assess perceptual trade-offs between categories of accident consequences, and also to assess perception of accident severity as a function of frequency (i.e., rate of occurrence).

PROPOSED DEFINITION OF ACCIDENT SEVERITY

Although a multitude of dimensions could be used to define "accident severity," practical considerations dictate that the actual number of dimensions should be kept to a minimum in order to facilitate the conduct of a perception survey, as well as to ease the computational requirements in drawing "fuzzy inferences" from the perception data. The selected

dimensions, nevertheless, should encompass the full range of consequences of potential accidents involving dangerous goods.

Based on these considerations, it is recommended that accident severity should be defined using five key dimensions. Although they may be subject to revision based on future survey results, the recommended dimensions at this stage are the following:

- o Direct out-of-pocket costs
- o Relocation impacts
- o Injuries
- o Deaths
- o Environmental impacts

Direct out-of-pocket costs include losses incurred by the transport company and shippers, property damage suffered by residents, as well as the full costs incurred by government agencies and claims paid by insurance companies. Also included in this category are the direct relocation costs incurred by all parties (e.g., residents, transport company, insurance companies, government agencies) during temporary evacuation (e.g., in case of fire or gaseous releases) or more permanent dislocation (e.g., in case of environmental contamination), as well as out-of-pocket health costs and clean-up costs associated with hazardous spills.

The remaining impact categories, therefore, concern the severity of each type of occurrence as perceived by the public, independent of the monetary compensation involved. In the case of relocation impacts, it is hypothesized that the public perceive accident severity as a function of intangible effects such as pain, discomfort and inconvenience, irrespective of the direct costs that they know they are going to be compensated for by either the transport company, insurance companies or other government agencies. In the case of human injuries and deaths, rather than taking a

"value of life" approach, it is hypothesized that the public's perception of the severity of an accident is affected by the extent of injuries and deaths involved, again irrespective of the actual amount of compensation paid to accident victims and their families. Similarly, it is hypothesized that the public attach a value to the natural environment that cannot be reduced to direct clean-up costs or imputed damage values.

It is, of course, recognized that separating out-of pocket costs and non-monetary aspects of accident consequences is not without problems. However, it is believed that public perceptions can be captured more accurately on a multi-dimensional scale where each dimension is treated independently, than the case where all accident impacts are reduced to their direct or imputed monetary values. Without denying the difficulties associated with this somewhat artificial separation of monetary and non-monetary aspects of the same impacts (e.g., out-of-pocket costs from the pain and inconvenience associated with relocation), the concept underlying the position adopted here can be illustrated quite simply. Take the example of two accidents, each involving one million dollars worth of damages. The first involves only property damage while the second involves \$500,000 of property damage and \$500,000 paid in compensating the accident victim's family. The public is likely to perceive the latter accident much higher on a severity scale. In the multi-dimensional framework adopted here, both these accidents will be identical on the first "out-of-pocket cost" dimension while the public can still reveal their perceptions of the respective severity measures in evaluating the other dimensions of the problem which are treated independently of the monetary costs.

MEASUREMENT SCALES

Of the five dimensions defined in the previous section, only the direct out-of-pocket costs and deaths can be measured using single, absolute scales (i.e., dollars for the former and number of deaths for the latter). The other dimensions require more qualified definitions in order to be adequately described. For example, relocation impacts can be measured by the number of people requiring relocation, combined with both

spatial and temporal qualifiers in order to provide a more complete picture of the relocation impacts. Similarly, the number of injuries should be qualified by type and environmental impacts by both type and duration.

The lack of absolute scales for each of the proposed dimensions of accident severity is not a constraint for the use of these dimensions in fuzzy set analysis. As long as particular states or conditions can be described (linguistically, graphically or otherwise), their corresponding membership in a given fuzzy set (e.g., severe or somewhat severe) can be measured. In other words, membership in a fuzzy set can be defined for a "state" defined in terms of a collection of impacts, each described in sufficient detail by absolute values and/or linguistic qualifiers, as well as for precise point estimates such as a million or a ten million dollar accident.

As noted earlier, a selection of any number of dimensions to define accident severity requires certain compromises. The more dimensions there are (as long as they can be clearly and independently defined) the more accurately a complex accident situation can be described and trade-offs examined between different types of consequences. However, since the number of different possible states or vectors of accident severity is a function of the number of possible values for each dimension and the number of dimensions included in the definition, the set of all possible states of accident severity can very quickly become unmanageable. This can create problems in both the measurement of perceptions at the survey stage and the computations in subsequent analysis of the survey data.

At this stage, it is felt that at a minimum each of the five dimensions defined above should be described by three non-zero values. A set of proposed values for each dimension is provided below.

DIRECT OUT-OF-POCKET COSTS

- o Minor costs: < \$10,000
- o Medium costs: \$10,000 to \$1,000,000
- o Major costs: >\$1,000,000

RELOCATION IMPACTS

- o Minor impacts: up to 100 people inconvenienced for up to a few hours
- o Medium impacts: up to 1,000 people having to be relocated at least overnight
- o Major impacts: over 1,000 people having to be relocated overnight

HUMAN INJURIES

- o Minor impacts: few minor injuries
- o Medium impacts: many minor injuries and/or a few major injuries, most of which can be corrected
- o Major impacts: multiple permanent injuries many of which cannot be corrected

DEATHS

- o Minor impacts: 1 or 2 operating personnel
- o Medium impacts: a few deaths including 1 or 2 innocent bystanders
- o Major impacts: multiple deaths including a number of innocent bystanders

ENVIRONMENTAL IMPACT

- o Minor impacts: minimum short-term damage
- o Medium impacts: some major damage but no long-term effects
- o Major impacts: major damage including long-term effects.

APPLICATION OF FUZZY SETS

Using the five dimensions and the corresponding scales derived above, any given accident can be defined as follows:

$$X(a(i), b(j), c(k), d(m), e(n))$$

Where:

- a(i) is the level of cost impact
- b(j) is the level of relocation impact
- c(k) is the level of injuries
- d(m) is the level of deaths
- e(n) is the level of environmental impact

Higher values of i, j, k, m and n represent increasing impacts, while zero values represent no impact on that dimension.

For each accident, defined in five dimensions, membership values in a given fuzzy set can then be measured. For the fuzzy set "severe," a survey question can take the following form:

- o On a scale of 0-1, how strongly do you believe that an accident with the following set of consequences is a severe accident?

Thus, the membership function $M_S(a(i), b(j), c(k), d(m), e(n))$, will be a mapping in the five-dimensional space, $i \times j \times k \times m \times n$.

If all five recommended dimensions of accident severity were included in the analysis, and each dimension had 3 non-zero as well as the zero state for possible values, there would be a total of 1,024 possible combinations of accident consequences. It would clearly not be feasible to measure public perceptions with respect to all of these possible combinations, therefore, alternatives to a 100% sampling procedure for each individual would have to be considered. Since in each dimension, the variable values independently describe accident consequences of increasing severity, the following relationships would hold true:

$$S(a(i), b(j), c(k), d(m), e(n)) \geq S(a(i^1), b(j^1), c(k^1), d(m^1), e(n^1))$$

$$\begin{array}{l} \text{if } i \geq i^1 \\ \quad j \geq j^1 \\ \quad k \geq k^1 \\ \quad m \geq m^1 \\ \text{and } n \geq n^1 \end{array}$$

It follows from the above relationship that if a given vector of accident consequences has a membership with respect to severity equal to 1, than all other vectors of consequences with impacts at least as large as the initial vector over all five dimensions will also have a membership equal to 1. For example, if an accident which results in major impacts in the death dimension and zero impacts in all other dimensions has a membership of 1 with respect to the linguistic descriptor severe, than all accidents with a major level of impact in the death dimension will have a severity membership equal to 1.

Because of the relationships described above, data collection requirements for fuzzy set analysis of accident severity could potentially be reduced to a manageable level. Furthermore, membership values could be used to classify accidents into a limited number of categories which reflect different levels of perceived severity.

For example, the following categories of accidents could potentially be defined for various ranges of membership values with respect to fuzzy set "severe":

<u>Category</u>	<u>Membership</u>
o minor	0 - .2
o minor/moderate	.2 - .3
o moderate	.3 - .5
o moderate/major	.5 - .6
o major	.6 - .8
o major/catastrophic	.8 - .9
o catastrophic	.9 - 1

The membership values presented above are for illustrative purposes only. the actual values used would depend upon the determination of natural groupings of accident vectors resulting from a perception survey on accident severity. Accident vectors which have one or two minor cost, relocation, injury and environmental impacts and no deaths may fall into the minor category of accidents. Similarly, accidents which have a major impact with respect to deaths and any other values on the dimensions may all be categorized as catastrophic.

INTEGRATION WITH ACCIDENT FREQUENCY

The classification of accidents into specific categories depending upon perceived severity could be examined in combination with accident frequency using fuzzy set analysis to measure perceptions with respect to the acceptability or unacceptability of risks associated with the transportation of dangerous goods. Using this analysis on the fuzzy set "acceptable risks," questions could be posed in the form:

- o On a scale of 0 to 1, how strongly do you believe that the risks associated with an accident of the type described below are unacceptable risks if on average such an accident occurs once every five years?

Below the question, the accident type would be described in terms of the dimensions and variables used to develop memberships with respect to accident severity.

In the analysis, the following characteristics would hold:

- o Accidents with similar membership values with respect to the fuzzy set "severe" would exhibit similar membership functions in the fuzzy set "unacceptable" when plotted against frequency.
- o For a given accident frequency, accidents with higher severities would be less acceptable.
- o For a given accident severity, acceptability would decrease with increases in accident frequency.

These characteristics could make it possible to develop data collection strategies that focus on areas of the membership curves where the greatest change is expected.

APPENDIX C

THE USE OF SUBJECTIVE PROBABILISTIC
ESTIMATES IN RISK ASSESSMENT

APPENDIX C

THE USE OF SUBJECTIVE PROBABILISTIC ESTIMATES IN RISK ASSESSMENT

In recent years there has been great interest in the use of "expert judgement" or estimates by "subject matter experts" to establish the probability of various events for which no hard data exist. The dominant factor driving the use of subjective estimates or probability has been the need to estimate the probability of accidents in nuclear power plants, but the methods and problems of the use of subjective estimation in general, whether of probability, risk, hazard, etc.

This paper outlines conventional (as distinct from fuzzy) approaches to subjective scaling, several methods currently in use for estimating error or fault probabilities and some observations on the psychology of human judgement which indicate that conventional "crisp" subjective estimation is to be mistrusted, especially when complex decisions are required.

CLASSICAL METHODS OF CONSTRUCTING SUBJECTIVE SCALES

The theoretical basis of measuring the magnitude of subjective feelings, sensations, or estimates is due to Thurstone (1959), and has been described in detail in many standard psychophysical texts (Torgerson (1958); Guildford (1954)). The basic concepts underlying the construction of subjective scales is rather simple. If a given stimulus (S_1) is repeatedly observed its effect on the observer is not constant. For example a light of fixed brightness will sometimes appear brighter than at other times. It is assumed that the distribution of the magnitude of the internal (mental) events caused by a fixed physical stimulus is distributed as Gaussian normal. If a second stimulus of slightly greater physical intensity (S_2) is repeatedly presented, it will give rise to its own distribution of subjective effects, also Gaussian normal. If S_1 and S_2 are close together in physical magnitude the two subjective distributions will

overlap. As a result the greater stimulus S_2 will sometimes be judged to be less in magnitude than the lesser stimulus S_1 . If we make the further assumption that the variance of the two internal distributions are equal and that there is no correlation between the momentary values of the random noise which produces a stochastic distribution from a fixed variable, then by choosing the units of the hypothetical distributions appropriately we can equate the proportion of trials on which S_1 is judged greater than S_2 with the extent to which the two distributions overlap. Thus the proportion of times one stimulus is judged greater than the other is a measure of the distance apart of the psychological events caused by the different physical stimuli.

By extension any stimulus dimension can be scaled, providing that the proportion of times one stimulus is judged greater than the other can be measured, and the underlying theoretical assumption justified. For example, one might ask an observer which of two events was more risky, or more hazardous; or which outcome was more costly, more severe, or more intolerable. By a further extension the psychological distance apart of labelled categories such as "slightly risky", "moderately risky", "very risky" etc. can be measured.

To summarize, by measurements which are simply of the form "A is greater than B", (ordinal measurement), and with appropriate theoretical assumptions a much stronger scale can be constructed which is at least an equal interval scale, which, for example, it could be said that the distance from "slightly" to "moderately" was the same distance as from "moderately" to "very". A good account of such a scaling operation in a very practical setting is given in McDonnell (1969), although Torgerson and Guildford (op.cit) are more comprehensive.

The success of scaling depends on the methods used to elicit the magnitude of the subjective effects experienced by the judges. At one extreme this can be direct estimation. The judge is asked "On a scale of zero to 1000, where 0 is "no risk" and 1000 is "certainty of accident", what number could you associate with event X?" A slightly different

version would be, "If the risk associated with event X is 100, what number would you associate with event Y?"

Less direct methods are the Method of Paired Comparison or the Method of Ranking. In Paired Comparison, every possible combination of pairs of events is given to the judge, and the latter is asked to state which of each pair has the greater magnitude. This leads directly to an estimate of the proportion of times that event X is judged greater than event Y, and hence to an estimate of their psychological distance apart, as described earlier. The problem is that as the number of events of interest increases linearly the number of pairs groups much faster - the number of pairs is $N(N-1)/2$ which puts an intolerable burden on the judges, albeit that people are very reliable in their judgements.

To decrease the number of judgements, it is possible simply to ask judges to rank order all the possible events from highest and lowest on the scale of interest. For example, one could present people with a list of 20 events and ask them to arrange them in order from the most to the least hazardous. By combining the rankings from a number of observers, it is possible to estimate the proportion of times that event X is ranked higher than event Y, and so once again the necessary estimate of proportion is obtained which leads to the appropriate interval scale.

The overall conclusion is that a well established methodology exists for constructing subjective scales. Reliable scales can be constructed and their reliability estimated. The validity of a scale - whether it measures what it claims to measure - is a greater problem, but not insuperable. The main problem is that such scale construction is labour intensive and time consuming. There is no reason why such methods could not in principle be applied by hazard assessment.

SUBJECTIVE ESTIMATION: THE PROBLEM OF MAPPING

A greater problem arises in special cases, the problem of mapping scale values onto a variable in the "real world". Consider the problem of

estimating the probability of rare events, which is the core of Human Reliability Estimation in probabilistic risk assessment for the nuclear industry, where no objective data base exists.

By using an appropriate scaling method, one can establish what experts (or non-experts) consider to be the relative probability of specific events. For example, on a 100 point scale, an operator might judge that the probability of misreading a dial is 10, and the probability of failing to notice a faulty annunciator to be faulty is 30. The problem is how to convert the numbers "10" and "30" into a number in the range (0,1) to give an estimate of probability. Several models for this mapping are available in the literature, generally of the form

$$P = a + b \log(m)$$

where p is a probability, m the scale value, and a and b are constants. Two problems arise. One is that at least two empirical probabilities are required to anchor the scale, and such may not be available at least for probabilities of comparable magnitudes to the scaled events. (If they are too far removed the validity of the mapping becomes doubtful). The second problem is that, when all is said and done, the numbers in the range (0,1) have an appearance of accuracy which is largely spurious: they are no more accurate than the original "guestimates" of the subject matter experts who may actually have never seen any of the events.

There are at least 10 models for subjective probabilistic estimates, and these have recently been reviewed in the context of human error by Schurman and Banks (1985). Several of them - for example SLIM-MAUDE, STAHR, and SHARPE, could almost certainly be adopted to the estimation of hazard and risk. But as Schurman and Banks point out, in the end they all rely on "expert judgement", and remain estimates which usually include estimates of events of which the judges have no direct experience. As such the estimates must be regarded with great reserve. At least the use of fuzzy measures makes explicit the element of subjective vagueness in the judgemental process. The same criticism outlined here applies to such

procedures as the Delphi method, which may well reduce the variance of estimates without guaranteeing that the judgemental mean estimate is aligned with the mean of the objective values.

FACTORS AFFECTING HUMAN JUDGEMENT

A concise and interesting treatment of the psychological limitation of all human decision makers is given by Sage (1981). He lists 27 factors which are known to cause human to be less than optimal decision makers. Insofar as making judgements or estimates inherently involves decision, his account applies to all human estimation. Some of the factors are as follows:

1. Given a large amount of data a person tends to anchor estimates to some datum such as the mean, and make judgements relative to that datum, in a way which distorts the estimates.
2. Only information which is (mentally) easy to come by is used: data which are difficult to think of are ignored even if important.
3. The likelihoods of events are often estimated relative to one another and the absolute base rates are ignored.
4. Estimates are not revised as much as they should be in the light of new evidence.
5. Summarized data often have a much greater impact than raw data on which the summaries are based.
6. People often make decisions on the basis of less evidence than is available, stopping data collection prematurely.
7. Easily recalled data are weighted more heavily than they should be.
8. Data which confirm expectations are often given greater weight than data which disconfirm expectations.
9. Strongly held values are often reviewed as facts.

10. People often express greater confidence in conclusions based on small samples than the size of the samples warrant. (This is sometimes satirically called "The Law of Small Numbers.")
11. The order of presentation of data affects the weight given to the data.
12. People underestimate high magnitudes and overestimate low magnitudes, and are poor at estimating range statistics such as variance.
13. People tend to collect data to confirm hypotheses rather than testing hypotheses.
14. The impact of evidence may be due less to the objective weight of the evidence and more to the social experience of past outcomes.

The remaining factors in Sage's list are of less direct relevance.

The overall picture which forces itself on the (hopefully unbiased!) assessor is that by and large humans are poor statistical decision makers. At the same time there are certainly some situations in which humans show behaviour which is so nearly optimal that the well-documented limitations on human judgement reported by Sage are not credible. The difference between situations which produce near optimal judgement and those which produce badly sub-optimal judgement is not well understood. Moray (1985) suggests that, in essence, the more a person has to think about his decision the less optimal it will be; while the more he can (because of his level of expertise) make the decision almost automatically the more optimal he will be.

CONCLUSIONS

1. It is possible, with care and the use of appropriate techniques, to obtain reliable and valid measures of subjective judgement. The application of the techniques require considerable expertise and cannot be done except by appropriately trained professionals.
2. The fact that precise numbers can be put on such estimates should not be taken to mean that the estimates are as precise on the numbers may make it appear.
3. If it can be shown that the psychological decision space of humans (experts or ordinary citizens) is more appropriately scaled by verbal labels such as "very", "somewhat", "slightly", than by numbers, the case for the use of fuzzy measurement would be strengthened. The present state of our knowledge leaves that conclusion as an assumption not an empirically established fact.
4. Under any measurement technique there are many sources of bias which may affect human decision making and human judgement.
5. This last conclusion applies equally to citizens, experts, and policy makers.

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APPENDIX D

ANNOTATED BIBLIOGRAPHY

BIBLIOGRAPHY

FUZZY SET THEORY

1. The Concept of a Linguistic Variable, and its Application to Approximate Reasoning, L. A. Zadeh. *Information Sciences* 8, 199-249 (1975).

This paper defines several fuzzy connectives such as "and" "or", using the max/min complement set of operators. It then proceeds to describe the "extension principle" and its applications to approximate reasoning based on linguistic variables.

2. A Fuzzy Sets Based Linguistic Approach: Theory and Applications, Piero P. Bonissone. *Approximate Reasoning in Decision Analysis*: M. M. Gupta and E. Sanchez (eds), North Holland Publishing Company, 1982.

Fuzzy sets theory and fuzzy logic constitute the basis for the linguistic approach. Under this approach, the variables can assume linguistic values. Each linguistic value is given a label and a meaning. The label is a sentence of a language. The meaning is a fuzzy subset of the universe of discourse. Models based on this approach can be constructed to simulate approximate reasoning. The implementation of these models presents two major problems namely: how to associate a label to an unlabelled fuzzy set on the basis of semantic similarity, and how to perform arithmetic operations with fuzzy numbers. For each problem, a solution is proposed. Two illustrative applications to decision analysis and natural language processing are discussed.

3. The Theory of Fuzzy Decisions. Approximate Reasoning in Decision Analysis, Kofi Kissi Dompere, North Holland Publishing Company 1982.

In this essay, the theory of fuzzy decisions is presented as a natural development of the non-fuzzy decision theory. The development of the theory is viewed in terms of interaction between relevant criteria and constraints, given the information set and the space of relevant variables. It is thus set theoretic in approach. The nature of algorithms that may lead to optimal fuzzy decision principles are analysed and discussed.

4. Representation of Connectives in Fuzzy Reasoning: A View Through Normal Forms, I. B. Turksen and D. D. W. Yao, *IEEE Trans on SMC*.

The representation of the fuzzy connectives ("and", "are", "not", "if then") is re-investigated in the setting of fuzzy reasoning. The new approach differs from previous ones such as by Zadeh and Hisdal. The concern is based on the fact that the implications as well as other connectives are linguistic entities that are inescapably associated with fuzziness. The paper investigates the manner in which they introduce, or rather, add fuzziness into the statement in which they are included.

5. Fuzzy Set Theory: Past and Future - Advances in Fuzzy Sets, Possibility Theory and Applications. Paul P. Wang, Sam Earp and Enrique H. Ruspini, Plenum Press, N.Y., 1983.

This essay reviews twenty four key papers in the area of fuzzy sets theory. Emphasis is laid on the analysis of imprecise concepts, which led to Zadeh's pioneering work.

6. Advances in Fuzzy Sets - An Overview. A. Kaufmann, 2, allée du Chêne, Corenc - Montfleury, 38700 - La Tronche, France.

This paper gives a summary of current results in application areas including approximate reasoning and decision making. The author makes a comprehensive study of over 700 papers by over 600 scientists. A concise review of the theory of fuzzy sets is also given.

7. Fuzzy Sets, Information and Control. L. A. Zadeh, 8 (1965) 338-353.

This is the paper which originated the theory of fuzzy sets.

PROBABILITY THEORY

1. Event Probabilities and Impact Zones for Hazardous Material Accidents on Railroad, A.D. Little, Inc., For Transportation Systems Centre, Boston, May 1981.

Procedures are presented in this report for evaluating the probability and impact of hazardous material accidents in rail transportation. The significance of track class for accident frequency and speed for accidents are quantified. Special attention is given to the analysis of track-caused accidents. Quantitative estimates are provided of the amount of hazardous material release per accidents as well as the area affected by these releases. An error analysis is made of the various probabilities.

2. Assessment of the Risk of Transporting Propane by Truck and Train, Prepared for U.S. Department of Energy by Battelle Memorial Institute/Pacific Northwest Laboratories, March 1980.

This report is part of a series of assessments of the risk of transporting potentially hazardous energy materials published by Battelle. The methodology for assessing risk is based on a fundamental equation which measures the total system risk as a sum of all of the risks of all accidental releases of material. The risk of an individual release is a product of the consequences of the release and the probability of its occurrence. Four components are needed to provide input data for solution of the equation: the system description, release sequence identification, release sequence evaluation, and risk calculation and assessment. The results of the report gives probabilities for the number of accidents per year by mode and the expected consequences of each type of accident. A spectrum is developed which shows

the expected frequency in events per year of events versus the number of fatalities that are predicted from those events. Sensitivity studies were also performed to determine the most important contributors to risk. The analysis showed that the risk for propane shipments is less than many other commonly accepted risks in society.

3. Hazardous Material Transportation Risk in the Puget Sound Region, W. B. Andrews et al, Battelle Pacific Northwest Laboratories, Richland Washington, 1981.

This paper summarizes results of a study performed by Battelle, Pacific Northwest Laboratories for the Transportation System Centre to determine public safety risks of transporting hazardous materials in the central Puget Sound Region of Washington State. The risk assessment methodology used in this case study was developed by Battelle, Pacific Northwest Laboratories and has been applied to shipments of many hazardous materials. This paper considers primarily truck and rail transport and selects a limited number of hazardous material classes for detailed analysis. Commodity risk spectra were developed for the selected commodities showing the number of fatalities by the estimated frequency (measured in events per year resulting in no more fatalities). The risk spectrum for the hazardous materials transported in the Region were then compared with other natural events which cause fatalities.

4. An Approach to Estimating Probabilities for Transportation Related Spills of Hazardous Materials, C.A. Menzie, EG&G, Massachusetts, Environmental Science and Technology, Volume 13, No. 2, February 1979.

An approach to estimating probabilities of transporting related spills of hazardous materials is described. The approach involves determining accident rates for appropriate modes of transportation and then determining the fraction of accidents that results in spills. Spill probabilities are then estimated from equations based on the Poisson distribution. An example is presented on how the approach may be used to estimate spills associated with chemical plant operations. However, the approach may also be used in determining probability of spills for whole classes of chemicals, or within certain geographical areas. Such information could be used to design more appropriate hazardous materials spill prevention, counter measure, and control plans.

5. Estimating the Risks of Transporting Hazardous Materials by Rail in Canada and the United States, S.J. Doswell, I.H. Uhm, R. De Malherbe, M.C. De Malherbe. A paper presented to Canadian Transportation Research Forum, Banff, Alberta, June 1984.

This paper presents an overview of the subject of risk analysis and its application to the field of hazardous materials transportation. The basic concepts of risk estimation and how they apply to transportation review. Data on hazardous material accidents, releases and transportation activity is presented, assessed, and statistically analyzed

using normal and Poisson distributions. Weaknesses and historical problems in Canada with such data are highlighted and future needs, directions and policy implications are outlined and discussed.

6. An Assessment of the Risks of Transporting Liquid Chlorine by Rail, W.B. Andrews, et al, Specific Northwest Laboratory, Richland Washington, March 1980.

This report presents the risks of shipping chlorine by rail. This is one in a series of eight reports on the risks of transporting energy materials. The risk model uses two equations. The first is a fundamental equation which says that the total system risks are the sum of the risks of all accident releases. The second equation is the expansion of the risks from an accident which is calculated as the product of the probability that the release sequence will happen during transport, the consequences of the material release and the probability of encountering a particular set of weather conditions within a population zone. The risk spectrum for shipments of chlorine is then developed which is a plot of the expected frequency (in events per year) versus the number of fatalities that are predicted from those events. The curve shows that, for the 1985 shipping level used in the analysis which is an average shipping quantity of 90 tons going an average distance of 450 kilometres, about one accident per year will occur, which results in one or more fatalities from the release of chlorine.

7. An Assessment of the Risks of Transporting Gasoline by Truck, R.E. Rhoads, et al, Battelle Specific Northwest Laboratory, Richland, Washington, November, 1978.

This report presents the risks of shipping gasoline by truck as part of a series of assessments of transporting energy materials. The risk assessment methodology has been described above in the previous study by these authors. Again a risk spectrum of the shipment of gasoline by truck is produced. The risk spectrum is the plot of the expected frequency in events per year, in events versus the number of fatalities predicted from those events. The curve shows that for the 1980s shipping levels used in the analysis (average shipment quantities of 8,400 gallons, and an average shipment distance of 50 miles) about 25 accidents resulting in one or more fatalities from the release of gasoline in an accident are predicted to occur in each year. In this study as in other studies in this series, the shipping risks are compared to other risks in society. Two possible methods of reducing the risks from gasoline releases in tank trucks were investigated: making the tank ten times more resistant failure by puncture, impact and abrasion and insulation of an accident-activated fire suppression on all tank trucks. The first method is expected to decrease the expected number of fatalities to nine per year and the second can potentially reduce the expected number of fatalities to less than one per year.

8. Development of a Systems Risk Methodology for Single and Multi-Modal Transportation Systems, U.S. Department of Transportation, Research and Special Programs Administration, July 1979.

The objective of this study were the development of a quantitative procedure for the predictive risk assessment of a given or proposed transportation system, and for evaluating the effects of certain major factors on the safety of the system. Three modes of transportation were covered within the scope of the program; air, highway and railway modes. The system risk model analyzes the safety of a transportation system in terms of expected frequency or rate of accidents and requires the tools and concepts of probability theory. This development of a system risk methodology also serves to identify missing information that is important in advancing system safety. The basic risk model is essentially composed of two parts: the evaluation of the frequency of all conceivable major faults or incidents in a system and the determination of the proportion of these faults that will cause accidents of a specified severity or type. The identification of the faults and the determination of their occurrence is accomplished systematically through fault free techniques and the determination of the conditional accident probability is done systematically through the use of entry free analysis.

GENERAL

1. State of the Art Review - Risk Analysis, Transport Dangerous Goods Directorate, Transport Canada, January 1981.

This report briefly outlines some of the major methodologies of risk available currently available including suggested usage, an explanation of the methodologies, limitations and other comments of importance. A bibliography of each methodology is included.

2. The Intercity for Hire trucking of Dangerous Goods in Canada, Transport Dangerous Goods Branch, Transport Canada, April 1982.

A summary of an investigation into the volume of dangerous goods transported by the for-hire trucking industry. Information regarding dangerous goods frequently transported, yearly changes in traffic trends, provincial handling of dangerous goods and the magnitude of dangerous goods transport relative to the overall for the trucking industry are provided. The data for this study is extracted from Statistics Canada For-Hire trucking survey.

3. The Transport of Dangerous Goods by Rail in Canada, Transport of Dangerous Goods Branch, Transport Canada, June 1982.

This study was prepared to determine the amount of dangerous goods transported across Canada each year and to look specifically at the the specific commodities that pose the highest risk to both population and property, should an accident occur. Included in this report are inter-provincial flows of dangerous goods by commodity class.

4. Risk Management Guide, G.J. Burstow, EG&G Idaho, Inc., June 1977.

This report provides guidance in risk and cost/benefit analysis, projection of large consequence - low frequency events, determination of the costs, and allocation of resources within the safety organization. The risk analysis techniques discussed in this report are primarily actuarial (instances of specific accident rates from general data) rather than probabilistic. It helps answer the questions of whether a company should be spending more time on prevention of large consequence events or on small, more frequent accidents, and whether more effort and resources should be concentrated on a specific type of hazard.

5. Risk Assessment of Air Versus Other Transportation Modes for Explosives and Flammable Cryogenic Liquids Volume 1; Risk Assessment Methods and Results, ORI Incorporated, for U.S. Department of Transportation, December 1979.

This report describes a method for assessing the comparative risks of transporting hazardous materials by alternative routes and modes. The method is then applied to the transport of Class A explosives and liquid hydrogen between specific origin destinations, testing the air-highway modal combination with alternative combinations of highway, rail, and marine modes. The risks were found to be highly route-dependent; however, for those routes selected, the air-highway modal combination showed generally lower risks. Rerouting or improvement in terminal operations showed the greatest opportunity for risk reduction.

6. Perceived Safety of Transporting Hazardous Materials, R.T. Reese, E.W. Sheppard, Sandia National Laboratories, Transportation Technology Centre, New Mexico, for U.S. Department of Energy, 1981.

This paper addresses an apparent anomaly in the transportation of hazardous materials which involves the issue that the level of safety as set out in the rules and regulations to limit the public's risk to "acceptable levels" is not the same as the perceived safety of the transportation activity. This paper tries to describe the relationship that exists between the many variables that appear to influence the public view of safety in hazardous materials transportation. A framework is developed to measure perception which is based on an equation which includes the variables technical feasibility, political palatability, social responsibility, utility assessment, media interpretation and familiarity as a function of time.

7. Relative Consequences of Transporting Hazardous Materials, R.T. Reese - Sandia National Laboratories, R.R. Fullwood, W.R. Rhyne and J.A. Simmons - Science Applications Inc., Oak Ridges, 1980

The objective of this paper is to discuss methods under study at the Transportation Technology Centre to develop a perspective on how technical measures of hazard and risk relate to perceptions of hazards and

risks associated with transporting hazardous materials. One aspect of the relative hazards problem discussed is the analysis of the possible affects associated with exposure to hazardous materials. This includes an outline of possible problems and controversies that could be encountered in the evaluation and comparison of hazards and risks and a description of the various measures of harm. The paper also calculates consequences for the effects created by a spill of hazardous materials using a mathematical formula.

8. The Methodologies of Hazardous Materials Transportation Risk Assessment, J.H. Wiggins Company, Redondo Beach, California, 1982.

This paper presents material that pertains to hazardous materials transportation from a project that was supported by the National Science Foundation identifying and focussing on improvements in particular areas of uncertainty in risk assessment methodologies. In this paper an overview is provided of the general risk assessment problem. A structured review of the types of methodologies employed in estimating the contribution to risk of different phases of a hazardous material incident and a review of procedures available for evaluating the significance of the risks estimated and the potential means for their mitigation are made. The risk estimation methodologies reviewed in this paper include statistical inference, fault tree modelling, analytical/simulation modelling, and formal subjective estimation of risk parameters.

9. General Concept of the Risk: Risk in Perspective, Professor Ann Whyte, University of Toronto. Proceedings of the Ontario Industrial Waste Conference, Toronto, June 1981.

In this paper the author discusses both risk assessment and risk perception. The process of risk assessment is described which begins with modelling what the risks are, defining which effects are to be included and finally uses a comparative framework to provide a yardstick for measuring risk. The last part of the paper deals with perceived risks as they compare with actual risks and looks at factors in public risk perception. One of the major results of the study was that the Canadian public's awareness far exceeds their knowledge about the technical and scientific and medical aspects of the hazards around them.

10. Risk Analysis in Transportation Systems, R. de Malherbe, A. G. Mamalis, M.C. de Malherbe, M. L. Giddings, Fortschritt - Berichte Der Udi Zeitschriften, Vol. 13, No. 18, 1981.

In this monograph, applications of risk analysis to problems in highway, railway, marine and pipeline transportation of hazardous materials are reviewed. The scope of the survey encompasses hazard identification and analysis, risk analysis and some safety measures developed to mitigate or reduce the hazards. In the appendix a review of the principal methods of risk and hazard analysis are discussed including failure mode and effect analysis, fault tree analysis, event tree analysis, risk-benefit analysis and probabilistic methods.

11. Decision Making for Low Probability Events: A Conceptual Framework, H. Kunreuther, International Institute for Applied Systems Analysis, Luxemburg, Austria.

This paper develops a framework for analyzing decisions for low probability events and discusses their policy implications. The framework highlights four inter-related components: type of information collected by individuals in making their decision, the decision process of individuals, implications of policies on specific groups and welfare implications. Examples from studies on natural hazards, health and safety problems are used to illustrate how this framework synthesizes descriptive models of choice with policy prescription. The paper concludes suggesting directions for future research.

12. "The Public" Vs. "The Experts", Perceived Vs. Actual Disagreements about Risks, B. Fischhoff, P. Slovic, and S. Lichtenstein. Paper prepared for the first annual meeting of the Society for Risk Analysis, at National Academy of Sciences, Washington, D.C., June, 1983.

This paper characterizes the full range of possible and probable sources of disagreement between members of the public and members of the community of technical experts about the risks of nuclear power. On the basis of this analysis it offers some suggestions for how a concrete resolution may be accomplished and where it is superfluous. The paper offers six reasons why disagreements between the public and the experts need not be interpreted as clashes between actual and perceived risks. Some of these reasons include misunderstanding, miscommunication and misinformation.

13. Risk Analysis: Regulatory Implications for Dangerous Goods Transportation, I.H. Uhm, Canadian Transport Commission. Paper prepared for presentation at the Canadian Transportation Research Forum, June 1983, Regina, Saskatchewan.

This paper provides a broad review of the existing theories, methodologies, and empirical studies of risk to derive meaningful regulatory implications. The paper reviews specific risk analysis methodologies applicable to dangerous commodities transportation including the Delphi Estimation Process, Bayesian Statistics, the Expected Value Model and Fault Tree Analysis. The paper goes on to discuss the requirements for regulatory agents to improve safety associated with dangerous commodities which includes: the development of a data base program, the development of risk analysis and evaluation programs and the implementation of safety programs. The components of each of these measures is discussed.

14. Use of Multi-Dimensional Utility Functions in Hazardous Shipment Decisions, Arthur D. Little Incorporated, Accident Analysis and Prevention Volume 10, Pages 251-265, 1978.

In this paper a realistic problem involving a decision related to the shipment of anhydrous ammonia by different transportation modes is formulated and solved utilizing decision theory. A methodology is presented for logically optimizing the choice of a transportation mode based on a particular decision-maker's individual preferences and perceptions regarding safety. The theory calls for the development for each mode, the probability of a certain number of spills in a given time period by a poisson distribution. The probable distribution function of the size of the spill is developed as a log normal density. The cost/impact analysis includes not only the actual unit costs of manufacture and shipment of the goods, but also any monetary costs paid by the company as a penalty for its deleterious effects on people, property and/or biophysical environment and any external effects. A utility function is developed to measure the costs/impacts in the risk analysis. The methodology is then applied to an example which involves the transportation of liquid ammonia; the choice of modes is barge, rail or pipeline. A brief assessment of the methodology shows that there are drawbacks with this methodology. The main one being the need for the decision-maker to develop a utility function for evaluating the impact of the exposure of humans to dangerous goods relations. Also, rigorous analysis requires a probability distribution of spill sizes which is not always available in detailed form. Finally, the conversion of spill volumes into the extent of damage to people, property and the environment requires several simplifying assumptions. There has been relative success however with the application of this methodology to choice of mode of transport in the shipment of hazardous chemicals but this methodology does not address the question of whether a given operation should be permitted in the first place.